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Insinööritieteiden korkeakoulu

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Internal curing of concrete

Diplomityö, joka on jätetty opinnäytteenä tarkastettavaksi diplomi-insinöörin tutkintoa varten.

Espoossa 30.03.2015
Valvoja: Professori Andrzej Cwirzen
Ohjaaja: TkT Karin Habermehl

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Tässä tutkimuksessa tarkastellaan betonin sisäistä jälkihoitoa. Betonin sisäinen jälkihoito on tuttu aihe jo Rooman valtakunnan ajoilta, jossa esimerkiksi kuuluisa Pantheonin temppeli on rakennettu kevytsoraa apuna käyttäen. Betonin ulkoinen jälkihoito kuten betonipinnan kastelu vaikuttaa vain tiettyyn syvyyteen asti betonissa, sisäisellä jälkihoidolla pystytän vaikuttamaan koko 3-ulotteiseen kappaleeseen.

Tavoitteena tässä diplomityössä on tutkia sisäisen jälkihoidon vaikutusta betonin puristuslujuuteen, taivutuslujuuteen sekä kuivumiskutistumaan verrattuna normaalisti valmistetun betonin vastaaviin ominaisuuksiin. Tavoitteena on myös selvittää, miten kevytsoran eri raekoot toimivat sisäisenä jälkihoito-aineena. Tässä diplomityössä betonin sisäinen jälkihoito toteutetaan kevytsoran avulla. Määrätty osa normaalista runkoaineesta korvataan kevytsoralla, jota kostutetaan yksi vuorokausi ennen betonin raaka-aineiden yhdistämistä. Kevytsoran pinta kuivataan paperimenetelmällä kostutuksen jälkeen pintakuivaksi. Kevytsora luovuttaa betonin raaka-aineiden yhdistämisessä sen sisään jääneen veden ja näin ollen betonin hydraatioprosessi paranee.

Tutkimusmenetelmänä tässä tutkimuksessa käytettiin kirjallisuuskatsausta sekä betonilaboratoriossa tehtyjä tutkimuksia. Yhteenvetona voidaan sanoa, että kevytsoran raekoot 0-2mm sekä 2-4mm toimivat parhaiten betonin sisäiseen jälkihoitoon. Näillä raekoilla saavutetaan lähes vastaavat mekaaniset ominaisuudet kuin pelkästään normaalilla kiviaineksella valmistetulla betonilla. Kuivumiskutistumisominaisuudet ovat paremmat kaikilla esikostutettua kevytsoraa sisältävillä betoneilla, joten sisäinen jälkihoito pienentää betonin kutistumista.

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ABSTRACT OF THE MASTER'S THESIS

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Internal curing was used already in the Roman times, for example the famous Pantheon building is done partly with internally cured concrete. The external curing of concrete such as fogging the surface only achieves the surface of the concrete, with internal curing the whole 3-dimensional microstructure of the concrete could be cured.

The objective of this thesis was to study the impact of internal curing on compressive strength, tensile/flexural strength and drying shrinkage. The goal was also to determine which grain sizes lightweight aggregates will be the best in internal curing use. In this thesis the internal curing is done with lightweight aggregates. The calculated amount of normal weight aggregate is replaced with lightweight aggregate, which is prewetted in the water for 24h before it was added to the concrete mix. Before it was added to the mix, the surface moisture of it was removed. Prewetted lightweight aggregate released its internal water to the concrete mix which improved the hydration process.

The used research methods include; literature review, definition of research program and experimental studies. The obtained tests results showed that the best grain size of lightweight aggregates for internal curing are 0-2 mm and 2-4 mm. The usage of these sizes enabled to produce concrete having similar mechanical properties to normal concretes but significantly reduced drying shrinkage.

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Keywords: internal curing, curing, lightweight aggregate, compressive strength, shrinkage

Foreword

First and foremost I want to thank God for giving us life and ability to study.
The time in the Aalto University has been good. I have grown both as person and as a student. I feel privileged to have the possibility tograduate from AaltoUniversity

Since my childhood, materials and surfaces have interested me. This topic was a good choice and inspiring to study because I value concrete as a building material and also as beautiful architectural particle. I firmly believe internal curing of concrete has a great potential to reduce cracking in concrete and therefore the whole life cycle of concrete.

Thank you especially for my supervisor, professor Andrzej Cwirzen , and to all the skilled people working in the concrete laboratory for giving me warm welcome and offering me help whenever I needed. I hope that with this thesis I have been able to give my contribution to the concrete development.

Espoo, 30.03.2015

Karri Kyllästinen

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Abbreviations

LWA = lightweight aggregate

NWA = normal weight aggregate

S = expected degree of saturation

α_{max} = expected maximum degree of hydration

RH = relative humidity

CS = chemical shrinkage

C_f = cement content of the mixture

Φ_{LWA} = absorption capacity of the LWA

M_{LWA} = the mass of dry LWA, that is needed to be prewetted to provide water to the

voids, which are created by the chemical shrinkage

1 Introduction

1.1 Background

The aim of this thesis was to investigate effects of internal curing of concrete provided by the prewetted lightweight aggregates used as an internal curing agent. Curing is one of the major issues regarding concrete production and therefore it is important to cure concrete with great care.

With right curing, concrete can achieve major benefits, such as

- Increased strength
- Better durability
- Reduced shrinkage and thus less cracking

The main problem related to a conventional external curing is that the whole three-dimensional microstructure does not get cured and saturated. It is only the surface that is being wet cured and the concrete interior remains unsaturated. This will create internal stresses and ultimately higher shrinkage and more cracking. Furthermore, mechanical properties can be worsened. With internal curing the entire concretre volume could be saturated with water originating from prewetted lightweight aggregates during the hydration process between cement and water.

1.2 Contents of the thesis

Chapter 1 is an introduction containing background information, content and description of current internal curing methods.

Chapter 2 contains the literature review addressing reasons why curing of concrete is required, theory and history of internal curing and also field experiences with trends and future perspectives.

Chapter 3 describes experimental studies done within this thesis. It includes description of initial and final studies. The performed and described tests include compressive strength test, flexural / tensile strength test and drying shrinkage test..

Chapter 4 in this chapter the results of the experimental studies are analysed and discussed and conclusions are formulated.

Chapter 5 presents topics requiring further studying.

1.3 Methods

There are currently two main methods for internal curing. The first method is use of prewetted lightweight aggregates and the second method is the use of super-absorbent polymers. This thesis concentrates on internal curing with prewetted lightweight aggregates.

In this thesis internal curing is made with Leca lightweight aggregate manufactured by Weber. Lightweight aggregates are prewetted for 24hours and then the surfaces of them are dried with paper towel method. There are four different mixture made with prewetted lightweight aggregate replacing calculated amount of normal weight aggregate. One mixture is reference mixture with no prewetted LWA. The gradations of used round lightweight aggregates are 0-2mm, 2-4mm and 4-8mm.

2 Literature review

2.1 Why curing is needed

”Curing is the maintenance of a satisfactory moisture content and a temperature in concrete for a period of time immediately following placing and finishing, so that the desired properties may develop.”(Kosmatka et al., 2003 pp. 219)

Concrete is cured to obtain desirable properties. The object is to maintain a favorable moisture and temperature conditions in a freshly mixed concrete. That allows hydration and possible pozzolanic reactions to occur so that the potential properties of concrete may be achieved. Curing is currently thought to be a one major concern regarding concrete studies.(Islam et al., 2011 pp. 22)

Curing has a great impact on a hardened concrete's properties. With a proper curing, durability, strength, water tightness, abrasion resistance, volume stability and resistance to freezing and thawing and deicers will increase. Especially slab surfaces are sensitive to curing, because the strength development and freeze-thaw resistance can decrease by large amount when it is not properly cured. (Kosmatka et al., 2003 pp. 219)

Chemical reaction called hydration takes place when Portland cement is mixed with water. Hydration has a great effect to the strength and durability of the concrete. When concrete is mixed, it contains often more water than is needed for the hydration process. Loss of water by evaporation can delay or prevent hydration process. The surface dries first, so it is particularly susceptible to evaporation and therefore to insufficient hydration. When temperature and moisture are correct, the cement hydration is rapid in the first days after concrete is placed. It is important to retain water in the concrete during the first days to prevent or at least to minimize evaporation. (Kosmatka et al., 2003 pp. 219-220)

When concrete is cured properly:

- Concrete becomes stronger
- Concrete becomes impermeable
- It is more resistant to stress and abrasion
- It is more resistant to freeze and thawing

When concrete is properly cured the improvement is rapid at early ages but continues with a slower pace after the start. Concrete mixtures with high cement amount and low water-cement ratios (<0,40) can require special curing. When cement hydrates with water, the internal relative humidity decreases causing the cement paste to self-desiccate (dry out) if there is no external water added. It is possible that paste can self-desiccate to the point that hydration stops. This can influence to the properties wanted from concrete, especially if the internal relative humidity goes as low as 80% within the first week. Therefore, it is highly important to cure concrete properly in order to get a good hydration process. (Kosmatka et al., 2003 pp. 219-220)

When concrete's curing is interrupted the strength development of concrete can continue for little time and then stops when the internal relative humidity is around 80%. If curing is then started again, the strength development can continue again but the potential of the concrete with constant curing may not be achieved. If there is loss of water in concrete, shrinking can take place. Shrinking creates tensile stresses to the concrete and if concrete has not achieved a high enough tensile strength it can cause cracking in the surface. Surfaces which are exposed need to be protected from evaporation. (Kosmatka et al., 2003 pp. 219-220)

Summarizing it is important to cure concrete in order to:

- Get a good hydration process
- Get desired properties of concrete
- More durable and resists abrasion better
- Get less shrinking and cracking
- Less permeable
- Better to withstand freezing and thawing

2.2 Internal curing – theoretical bases

The objective of internal curing is to prvocide a source of additional water so that the capillary porosity of the hydrating cement paste will remain saturated. This will reduce atuogenous stress and strains. This water will also maximise the hydration process and therefore potentially improve strength and reduce transport coefficients. Conventionally some water is also provided by external curing such as ponding or fogging. The external water can though penetrate only few millimeters into the concrete surface and the interioir of concrete remains uncured and undergoes susbstantial self-desiccation. (Bentz et al., 2011 pp. 5-6)

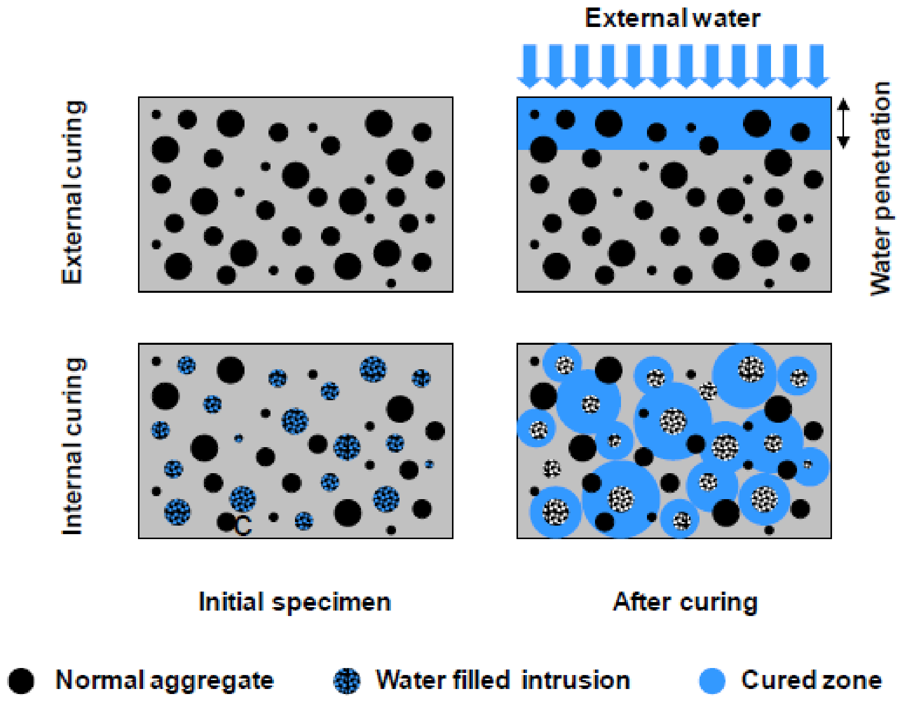


Figure 1. Illustration of the difference between external and internal curing using pre- wetted lightweight aggregate (Bentz et al., 2011 pp. 3)

The need for internal curing comes straight from the hydration process, as water and cement react together to form crystalline and gel products. These end products occupy less space than reactants did before the hydration. That leads to a chemical shrinkage as the end products occupy less space than the reactants. (Bentz et al., 2011 pp. 4)

One example of that kind of reaction is below, stoichiometry for the hydration of tricalcium silicate, the major component of Portland cement.

$$\begin{array}{ccccc} C_3S & +5.3H & \rightarrow & C_{1.7}SH_4 & +\ 1.3\ CH \\ 71.1 & 95.8 & & 107.8 & 43 \end{array}$$

With that reaction, the net reduction in volume is 9,6%.

Chemical shrinkage will produce similar physical shrinkage of concrete. After the cement paste sets and forms resistance to deformation, the chemical shrinkage, as no additional water is provided to the paste, will produce a self-desiccation, as partially filled pores will be created within the microstructure. The pore solution in the partially filled pores will create a capillary pressure. (Bentz et al., 2011 pp. 4)

The capillary pressure will then create a measurable shrinkage of the microstructure. When these strains and stresses become substantial enough, concrete is exposed to early-age cracking that will open paths for the ingress of deleterious species, which will compromise the desired design and service life of the structure. When capillary pressure increases, there will be a concurrent reduction in the internal relative humidity of the hydrating cement paste. (Bentz et al., 2011 pp. 5)

The goal of internal curing is to provide a proper amount of additional water with a good spatial distribution so that the whole microstructure remains saturated and autogenous stress could be minimized or totally excluded. (Bentz et al., 2011 pp. 6)

2.3 Internal curing in the history

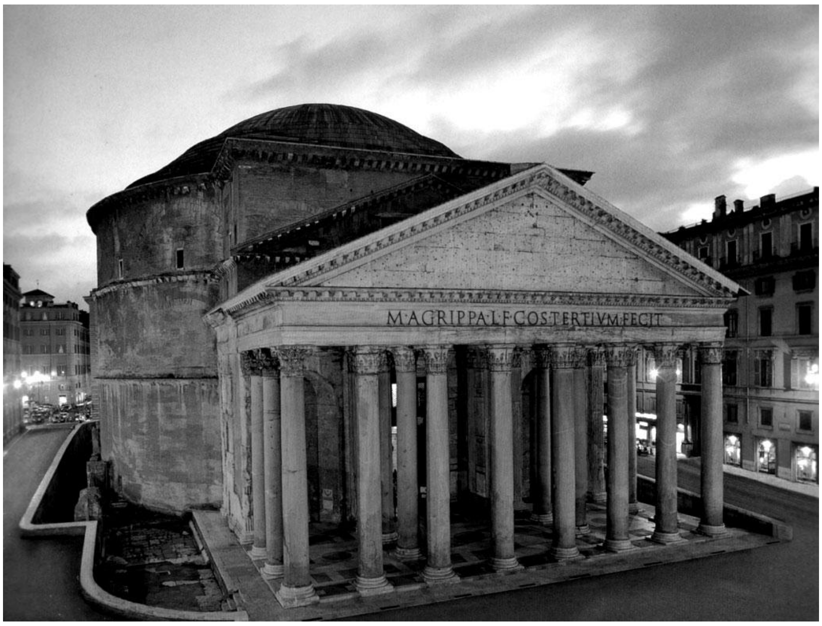


Figure 2. Patheon in Rome (2 000 years ago) was one of the first buildings made with lightweight aggregates. (Rise, J., 2011 pp. 4)

At the beginning, the internal curing was made unintentionally with the use of lightweight aggregate in order to produce lightweight concrete and to reduce the weight of concrete. Examples of these can be found in the ancient roman structures. The first recognition of the potential and purpose of internal curing was made after many years. (Kosmatka et al., 2003 pp. 219-220)

It was shown as early as in 1948 that autogenous shrinkage due to self-desiccation occurs when the water-cement ratio is below 0,42. All the water is consumed at that ratio. Some other researches have suggested that the water-cement limit can vary between 0,36 and 0,48 depending on cement type being used. When the water-cement ratio is much lower than 0,42 and there is no curing water available, the cement starts seeking internal water. (Hoff et al., 2010 pp 1-4)

Since the 1950s internal curing has been used inadvertently in lightweight concrete. Its potential for reducing self-desiccation in high-performance concretes was recognised in later in 1990s. Lightweight aggregates were mostly used in order to reduce the weight of the concrete structures. The aggregates were, however, often saturated to get a better workability and also because it was known that dry and porous aggregates would absorb water from a fresh concrete mix. It was found later that those structures had a great long-term durability and in-service performance. (Cusson et al., 2008 pp. 1-2)

In 1991 Philleo suggested the use of saturated lightweight aggregates into the concrete mix to provide internal source of water to replace that water which is consumed by chemical shrinkage during the hydration process. Philleo's suggestion got some recognition in the mid 1990s with a quite much work done with the LWAs to handle with the autogenous shrinkage. (Hoff et al., 2010 pp. 1-4)

Internal curing was also used in the late 1990s to reduce the early-age deformation of high-performance concretes. In this century the laboratory theory and researches had been taken to the practical field work. (Stutzman et al., 2010 pp. 1-2)

More recently there have been many construction processes where LWAs are successfully used for the purpose of internal curing. In 2005 in Hutchins, Texas there was about 190 000 m3 internally cured concrete used in a paving project. The reports showed marginal pavement cracking and the strength tests showed that the internally cured concrete's 7 day flexural strength reached 90% to 100% of that required 28 days, which was due to an improved hydration process. It was also found out that the compressive strengths of air cured cylinders were similar to those of wet-cured cylinders at all ages. In low permeability concrete, especially, external curing might not be enough to prevent self-desiccation in thick elements. It has to be remembered that with internal curing it is also recommended to use external curing in order to keep the surface continuously moist during the curing process. If the surface dries too much it can crack due to plastic or drying shrinkage. (Cusson et al., 2008 pp. 1-2)

2.4 Internal curing - field experiences

To this date internally cured concrete has been used in many different construction projects, such as:

- bridge decks
- pavements
- transit yards
- water tanks

At 2005, among the first documented studies, where internal curing was used, was a large raiLWAy transit yard in Texas, which required 190 000m3 of concrete. In this project, Intermediate sized LWA (178kg/m3 concrete) was blended with NWA. (Bentz et al., 2011 pp. 53)

There were several advances that was achieved with internally cured concrete in this project; over 15% increase in 28d strength, elimination of plastic and drying shrinkage cracking and a reduction in concrete unit weight that ultimately translates to reductions in fuel use and equipment. Since 2007 there has been made several crack surveys and only two or three cracks have been found. (Bentz et al., 2011 pp. 53)

In the state of Indiana, there were two bridges built in 2010 with internal curing. Those bridges were girder box bridges and in one case the topping slab was made from conventional mixture and in the other case it was made so that around 240 kg/m3 of fine LWA were used. Both decks were cured also with wet burlap and plastic sheeting for 7 days. After 40 days both bridges were walked and there was no cracks found in either one. (Bentz et al., 2011 pp. 54)

In the state of Indiana, there will be four bridges to be built using internally cured concrete in 2013. (Purdue University, 2013. Indiana using new concrete to increase bridge life)

2.5 Internal curing trends and perspectives

2.5.1 Future & Trends

As internal curing is taken more to the practise works, the research of it goes deeper and there are new areas to be explored. Two of the new topics regarding internal curing are:

- Utilization of crushed returned concrete fine aggregates as internal curing reservoirs
- Pre-wetting of the LWA with other materials instead of just water (Bentz et al., 2011 pp. 53)

2.5.2 Perspectives

Internal curing has a potential to make a great impact on durability and life-cycle costs. The cost of projects made in the USA (in Indiana and New York) have been approximately 0 % to 20 % higher, typically in the 10%-12% range, than those without internal curing. The reduced risk of cracking and chloride ingress should though contribute to greater durability of the structure and lower life cycle-costs and in summary it should have a positive economic value. (Bentz et al., 2011 pp. 64)

Additionally, besides these benefits, there is a need for additional quality control, additional costs which came from handling and wetting and then additional costs and energy consumption coming from the manufactoring of the LWA. In future as internal curing becomes more familiar and as there will be more field experiences the whole process of manufacture of the LWA will be more familiar. (Bentz et al., 2011 pp. 64)

2.6 The hydration process with internal curing

The internal curing is used in order to get a better hydration process. Internal curing provides additional water that increases the hydration and makes the microstructure denser. Recent studies have shown that mixtures containing LWA show an increase in heat release, which can be related to an increase in the degree of hydration. (Shin et al. 2009, pp. 12)

As the hydration process goes on, there are vapour filled voids created and the amount of them increases and the vapour filled voids exist in smaller and smaller pores corresponding with higher capillary stress. Internal curing is used to provide water from the LWA to fill the voids which are created by chemical shrinkage in order to reduce the cracking in the concrete. (Shin et al. 2009, pp. 3)

2.7 Interfacial transition zone

The interfacial transition zone (ITZ) is the zone between cement paste and the aggregate. The microstructure of the ITZ depends highly on the aggregate, especially its porosity and water absorption. With normal weight aggregates, because of the inherent size difference between aggregates and cement, there is a “wall effect”, meaning that there is a clearly two different layers, cement and the aggregates. Microstructural studies have shown that for LWA with a porous outer layer, there is no “wall effect”, and the zone is nearly continuous between cement and the LWA, along with the ability for cement hydration products to penetrate into the LWA. (Bentz,, 2009 pp. 285)

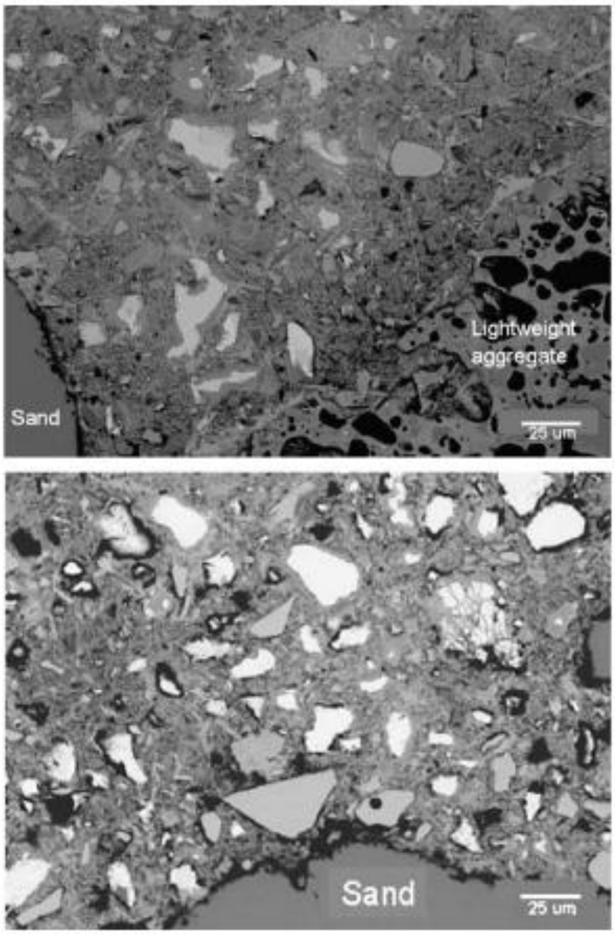


Figure 3. Top micrograph is for a mortar with internal curing and the bottom micrograph is for a mortar with only normal weight sand. (Bentz,, 2009 pp. 286)

For normal concrete the ITZ can be a problem as each normal weight aggregate is surrounded by a porous ITZ, their percolation or connectivity across the mixture might become a problem for durability and transport. Based on former studies, the general consensus is that for normal concrete the ITZs can provide a path for the ingress of deleterious species such as chloride ions. (Bentz,, 2009 pp. 285-286)

In LWAs the lack of distinct and more porous ITZ can contribute to reduced diffusion coefficients, as much as 70%. The greatest reduction is achieved when both the coarse and the fine aggregates are replaced with their counterpart LWA. Often only part of normal weight aggregate is replaced with LWA, which can still reduce the total volume of ITZ paste and have a great influence to percolation and chloride ion transport. The concrete service life is proportional to diffusion coefficients, so when the diffusion coefficients are reduced, that will increase the service life of the concrete. (Bentz,, 2009 pp. 285-286)

The measured penetration of chloride ingress is significantly less in mortars with internal curing compared to those without. The reduction in diffusion coefficients is likely due to a significant reduction in the volume fraction of percolated ITZ paste and better long term hydration. As internal curing provides great reductions in shrinkage and improves the stregth development at later ages, it can also enhance the resistance to the penetration of chloride ions and other deleterious species. (Bentz,, 2009 pp. 288-289)

2.8 Mechanism of internal curing and mixture proportioning

In internal curing the necessary additional water is provided from water-filled lightweight aggregates to prolong the time that saturated conditions are maintained in the hydration. The maintenance of these conditions will improve the degree of hydration and also minimize the development of autogenous stresses and strains that can lead to early-age cracking. (Bentz et al., 2011 pp. 7)

In the internal curing design, four questions must be considered:

- How much internal curing water is needed for a given set of mixture proportions?
- How far from the lightweight aggregate into the surrounding cement paste can the water move?
- The ability of water to leave the lightweight aggregate?
- The spatial distribution of the internal reservoirs (internal water) within the three-dimensional microstructure?

(Bentz et al., 2011 pp. 7; Schlitter et al., 2010 pp. 28)

2.8.1 Chemical shrinkage and autogenous shrinkage

Two terms must be defined when determining the needed amount of water for internal curing, which are the chemical shrinkage and the autogenous shrinkage. (Schlitter et al., 2010 pp. 28)

Chemical shrinkage is a process that occurs naturally and has been known for over 100 years. Chemical shrinkage is the primary cause of autogenous shrinkage and self-desiccation. Chemical shrinkage describes the volume reduction of the cement paste, which happens in hydration process as the volume of reactants is bigger than the volume of end products. This volume reduction can be as high as 8-10 %. Chemical shrinkage is often measured by placing cement paste in water and then the volume change of cement-water system is measured. The typical chemical shrinkage result is shown in the figure 4, for a paste with water-cement ratio of 0,30. (Schlitter et al., 2010 pp. 28-29)

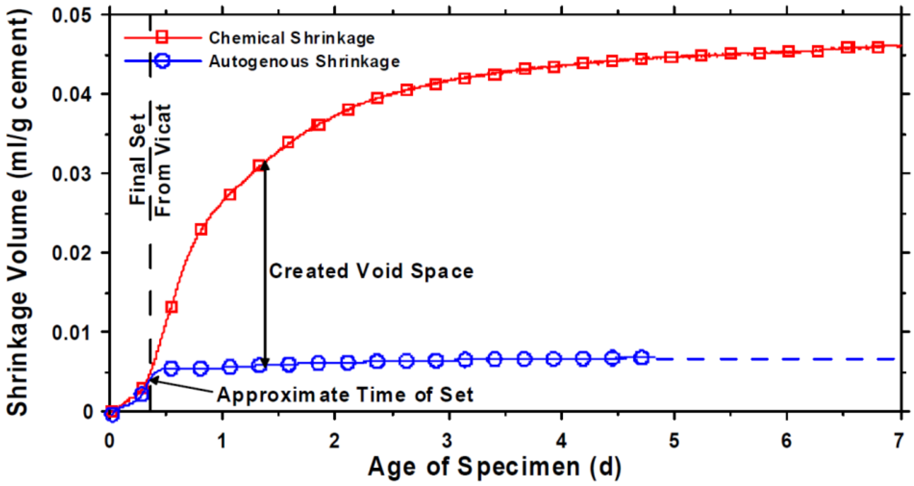


Figure 4. Chemical shrinkage and autogenous shrinkage volumes during the hydration process of concrete paste, which water-cement ratio is 0.30. (Schlitter et al., 2010 pp. 28-29)

Autogenous shrinkage is the reduction of external volume of a cement paste as it hydrates. Volumes of chemical shrinkage and autogenous shrinkage are the same before the set. That is because the system is fluid and the system collapses on itself as it shrinks. At the time after set, these two volumes diverge, as can be seen from the figure 4. As the matrix becomes more solid, it prevents bulk system from shrinking as chemical shrinkage occurs. That results to an underpressure in the system, which cavitates vapour -filled space in the pore system. These voids grow and penetrate even smaller and smaller pores as the hydration process goes on. The internal RH can be measured in the system to get an estimate of the pressure developing in the fluid. (Schlitter et al., 2010 pp. 29-30)

2.8.2 Amount of water needed for internal curing

The idea in internal curing using LWA is that the LWAs used as internal reservoirs can reduce the pressure in the pore fluid as they fulfil vapour-filled voids. (Schlitter et al., 2010 pp. 30)

Bentz and Snyder developed a method to estimate the needed amount of water and the amount of LWA to produce that water to the cement paste. (Bentz et al., 2011 pp. 7). The equation to calculate the required amount of dry LWA to get needed amount of water to curing. (Bentz et al., 2011 pp. 7) is shown below.

$$M_{LWA} = \frac{C_f \times CS \times \alpha_{\max}}{S \times \phi_{LWA}} \qquad \text{Eq (1)}$$

In the equation, M_{LWA} (kg/m3) is the mass of dry LWA that is needed to be prewetted to provide water to the voids, which are created by the chemical shrinkage, C_f (kg/m3) is the cement content of the mixture, CS (g of water per g of cement) is the chemical shrinkage of the cement, α_{max}(has no unit) is the expected maximum degree of hydration (from 0 to 1), S (has no unit) is the expected degree of saturation of the LWA (from 0 to 1) and Φ_{LWA} (kg of water / kg of dry LWA) is the absorption capacity of the LWA. (Schlitter et al., 2010 pp. 30-31)

2.8.3 LWA characterization

In order to work properly the pores in the LWA must be larger than those in the cement paste, then water can move from the LWA to the hydrating cement. At the moment there is not a standard test to evaluate absorption / desorption properties. Recent studies have also shown that water will move from the coarser pores to the finer ones. (Bentz et al., 2011 pp. 12)

2.8.4 LWA spatial distribution

It is important to know how the LWA is distributed in the microstructure. Even if a needed amount of LWA is supplied, if the distribution is insufficient, the performance of the concrete will not be good. When comparing the coarse and fine aggregate, it has been shown that fine aggregates have increased spacing between the aggregate. When the volume of LWA is increased, also the distribution is improved, which results to that larger fraction of paste is protected. (Schlitter et al., 2010 pp. 36-38)

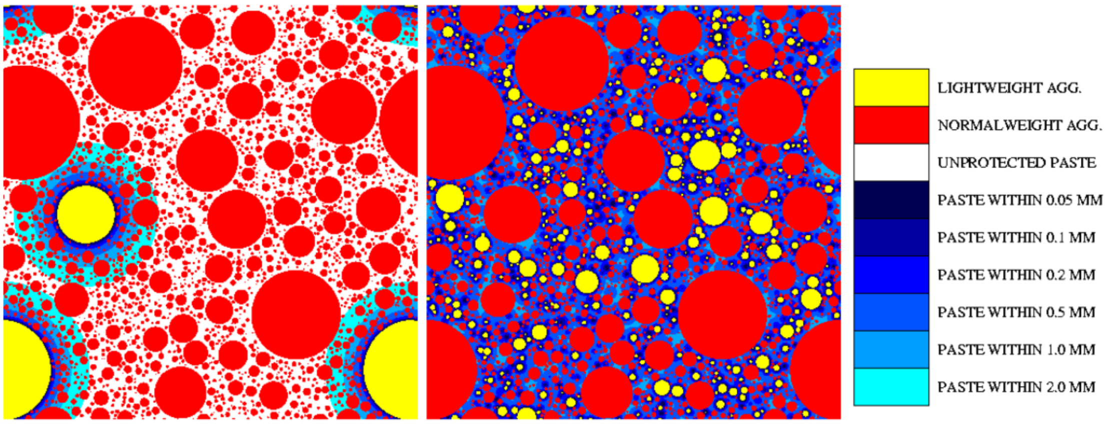


Figure 5. Illustration showing the volume of protected paste with coarse LWA on left and fine LWA on right. (Schlitter et al., 2010 pp. 39)

It has been studied that for concrete that had water-cement ratio of 0,4, distances that water travelled was following:

Hydration Age	Estimated Travel Distance of Water
Early (i.e., < 1 day)	20 mm
Middle (i.e., 1 day to 3 days)	5 mm
Late (i.e., 3 days to 7 days)	1 mm
Worst Case (i.e., > 28 days)	0.25 mm

Table 1. Estimated travel distances of water. (Bentz et al., 2011 pp. 7)

2.8.5 The ability of water to leave the LWA

Water leaves the LWA because there is underpressure (suction) in the pore fluid in the hydrating cement paste, which is created by chemical shrinkage and self-desiccation. The consequence of the moving water from LWA to the cement paste is that there is increase in internal relative humidity and increase in the critical pore size that remains prewetted. (Schlitter et al., 2010 pp. 31)

One of the basic principles for internal curing is that the largest pores will lose water first. Generally, LWA pores are larger than pores of the surrounding cement paste. Researches show that a majority of water is available to be lost at high relative humidity (RH>96%). LWA releases almost all of its water when a relative humidity of 92% is reached. That shows that the water will leave the LWA if high enough suction pressure exists or a low enough internal relative humidity. (Schlitter et al., 2010 pp. 31-32)

2.9 Mechanical properties of internally cured concrete

Mechanical properties of concrete are a major factor in early age durability performance. Because concrete is a heterogenous material, independent properties of the concrete paste and aggregate affect mechanical properties. (Schlitter et al., 2010 pp. 135)

The Lightweight aggregates are less stiff and strong compared to normal weight aggregates and that can cause slight decrease on the concrete strength. The impact to strength depends of the following factors:

- Type and quality of the LWA
- The size fraction used
- The amount of aggregate used
- Type and quality of the binder in the concrete

Generally, crushed LWAs are better for binder interaction than LWAs with a sealed surface. The transition zone of crushed LWAs is believed to be better compared to smooth and sealed surfaces. (Nesolite, 2010, Solitepaper)

2.9.1 Compressive strength

The effect of internal curing in the compressive strength depends on the specific mixture proportions, curing conditions and testing age. (Bentz et al., 2011 pp. 31)

Use of the LWA will decrease the compressive strength of the concrete in the beginning of its age. That is expected because the specific gravity of the LWA is lower, therefore leading to lower strength compared to concrete with normal weight aggregate. Previous studies have shown though, that the long-term compressive strength will increase when internal curing is used, so it is likely that concrete with LWA has a higher long-term compressive strength than concrete with normal weight aggregate. (Kerby, 2010 pp. 10)

Although the internal curing might improve the strength of the paste by providing additional water to the hydration process, the weakening effect by the weaker and softer aggregate can affect more to the overall behaviour, reducing the strength. (Schlitter et al., 2010 pp. 139)

In a recent study, where expanded shale was used as a LWA, it was shown that the initial strength of the internally cured concrete is lower than the mixture without internal curing, but after 2 weeks, the strength increased and was higher than the plain mixture's strength. The compressive strength was around 20 % higher than the plain concrete at later ages, because of the better hydration. (Dayalan et al., 2014 pp. 4)

Table 2. Mix designation of the study. (Dayalan et al., 2014 pp. 4)

Mix designation	% of replacement of Expanded shale
M0	0 %
M1	10 %
M2	15%
M3	20 %
M4	25 %

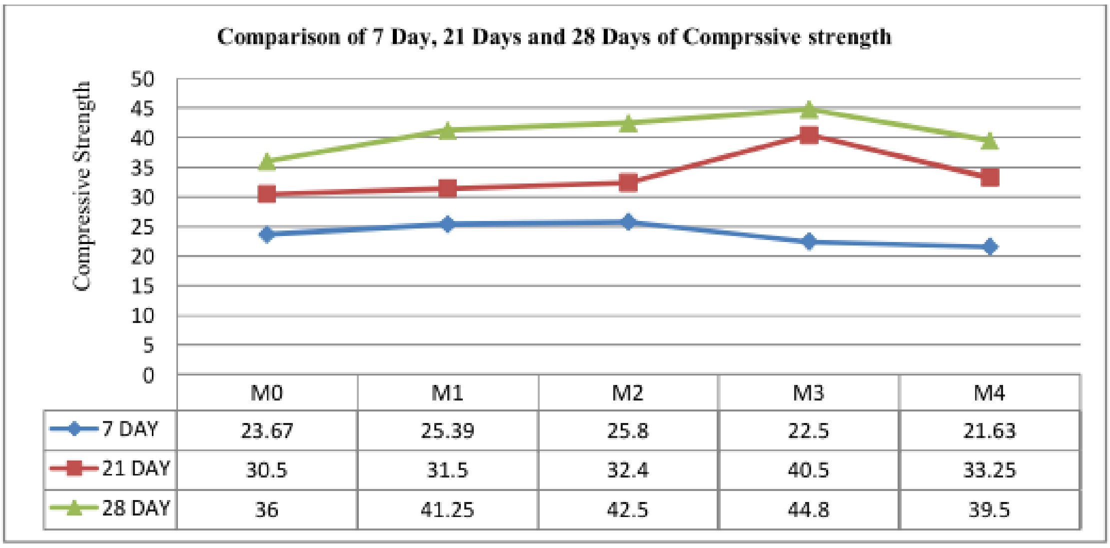


Figure 6. Compressive strength comparison after 7,21 and 28 days. (Dayalan et al., 2014 pp. 4)

2.9.2 Tensile / flexural strength

In general, the tensile strength of concrete with normal weight aggregates is slightly lower than the concrete with internal curing. The tensile strength seems to be similar compared to the compressive strength, the mixtures with highest amount of LWAs are weakest and the mixtures with no internal curing are strongest. (Schlitter et al., 2010 pp. 139)

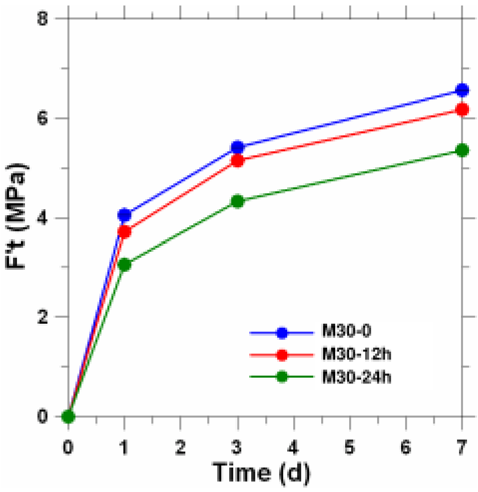


Figure 7. Tensile strength for a conventional and for two mixtures with LWA, 12 % and 24% respectively, % are of the total mass. (Shin et al. 2009, pp. 35)

2.9.3 Modulus of elasticity

In general, small amounts of lightweight fines increase the modulus of elasticity as larger amounts might decrease the modulus of elasticity. Slight decrease of modulus of elasticity can be also good as it can reduce cracking in the concrete. (Nesolite, 2010, Solitepaper)

When the amount of the LWA is increased the modulus of elasticity reduces, both early age and long-term. The same trend can be observed with compressive strength and tensile strength. This is explained, as the sand is replaced with softer lightweight material. (Schlitter et al., 2010 pp. 140)

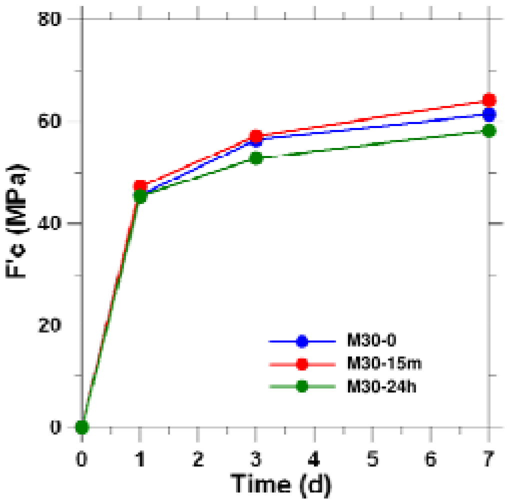


Figure 8. Modulus of elasticity for a conventional mixture and two internally cured mixtures, with 15% and 24% of LWA of total mass, respectively. (Schlitter et al., 2010 pp. 140)

2.10 Shrinkage of concrete with internal curing

2.10.1 Autogenous shrinkage

Autogenous shrinkage can be reduced by internal curing, as the pores in the LWAs, where the water is released, are larger than those in the cement paste. Also the amount of water and its spatial distribution are important factors. The increased degree of hydration and increased long-term compressive strenght also reduce autogenous shrinkage. (Geiker et al., 2004 pp. 6)

It has been shown in recent studies that properly proportioned volume of LWA can be used to reduce the unrestrained and restrained shrinkage in both sealed and unsealed conditions. (Henkensiefken et al., 2009 pp. 2-4)

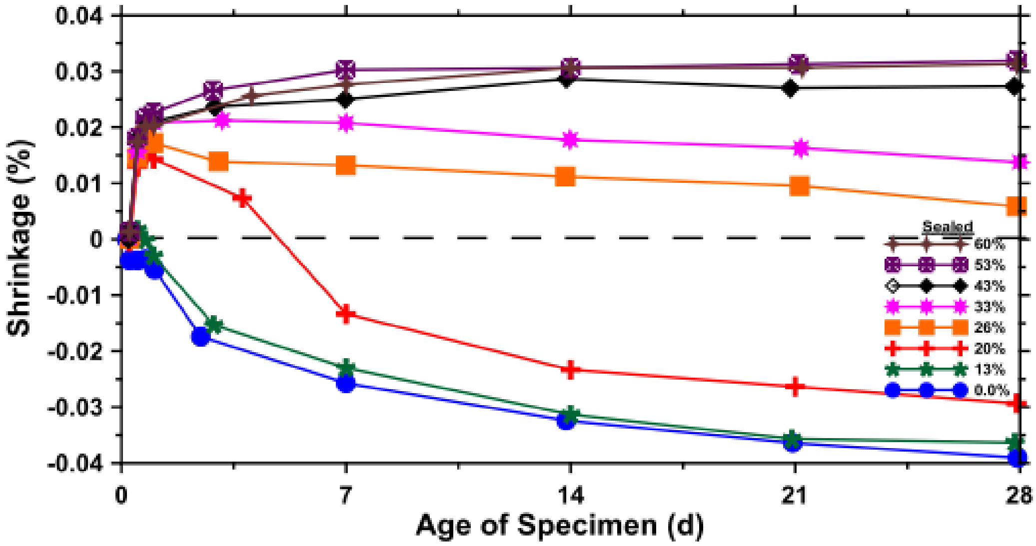


Figure 9. Unrestrained shrinkage of mortars with different volumes with LWA in sealed conditions. (Henkensiefken et al., 2009 pp. 2-4)

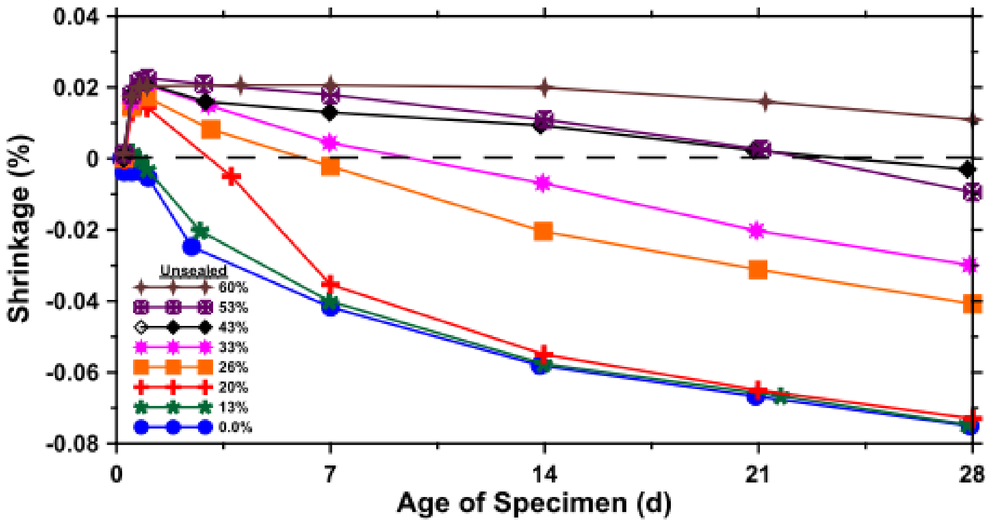


Figure 10. Unrestrained shrinkage of mortars with different volumes with LWA in unsealed conditions. (Henkensiefken et al., 2009 pp. 2-4)

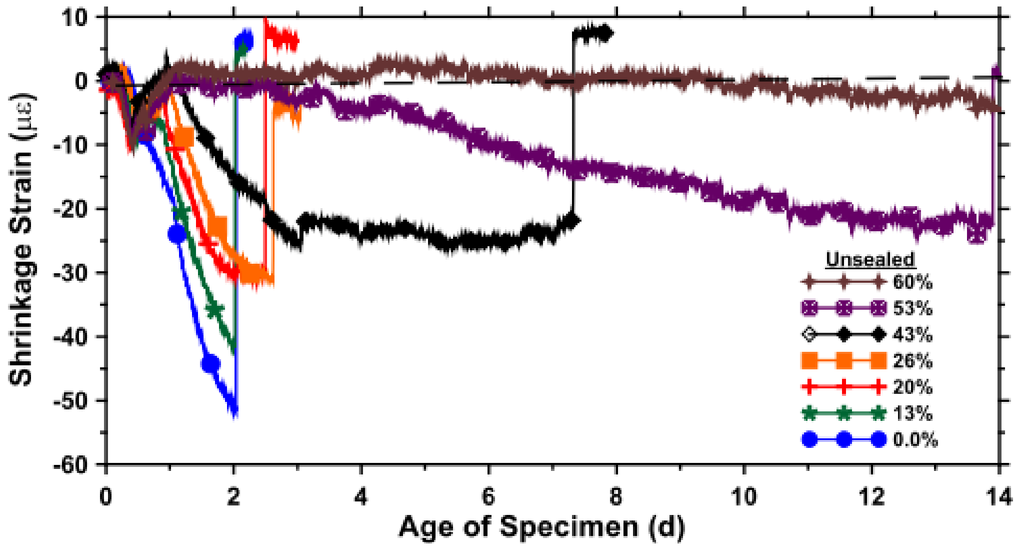


Figure 11. Restrained shrinkage of mortars with different volumes with LWA in unsealed conditions. (Henkensiefken et al., 2009 pp. 2-4)

In the figure above, the sharp vertical increase indicates crack. It can be noted that with sufficient volume of the LWA, cracking occurs much more later than without LWA. It has to be noted that aspects such as curing conditions, aggregate grading, paste properties and aggregate properties need to be considered. (Henkensiefken et al., 2009 pp. 2-4)

2.10.2 Plastic shrinkage

Between the time of placement and time of set the concrete can be susceptible to plastic shrinkage cracking. These cracks are unsightly and they can lead to an ingress of deleterious materials. (Henkensiefken et al., 2010 pp 1-6)

The mechanism of plastic shrinkage can be described in three phases. First, the cement and aggregates react together and water rises to the surface. This water is called bleed water and it is free to evaporate from the surface. (Henkensiefken et al., 2010 pp 1-6)

The second phase begins when the bleed water evaporates and liquid-vapor menisci forms to the surface and to the interior of the concrete. Because the capillary pressure, the particles are rearranged. Water from the LWAs is drawn out, because of its larger pores compared to the cement paste. When the pressure can no more decrease, the drying front recedes from the surface to the interior of the concrete, then concrete is the most susceptible to cracking. That is called the critical point. (Henkensiefken et al., 2010 pp 1-6)

In the third phase, drying front penetrates into the interior of the concrete and the path between the surface and the interior is gone. Both evaporation and settlement rates slow down. (Henkensiefken et al., 2010 pp 1-6)

Recent studies have shown that with sufficient volume of LWA, plastic shrinkage cracking can be reduced or eliminated. The supply of water from the LWAs can reduce the settlement which is accompanied with the evaporation. The volume of capillary stresses, which is developed during drying, is also reduced. Self-desiccation is also a concern, and the mixture needs to be properly proportioned, so that there is enough water to both plastic shrinkage cracking and cracking caused by self-desiccation and drying. (Henkensiefken et al., 2010 pp 1-6)

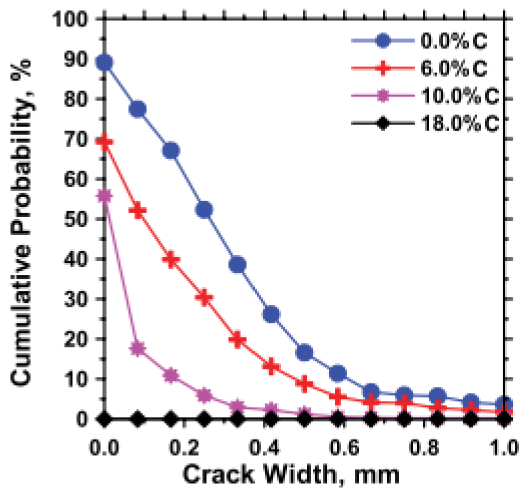


Figure 12. Distribution of crack width occurances with different replacement volumes of LWA. (Henkensiefken et al., 2010 pp 1-6)

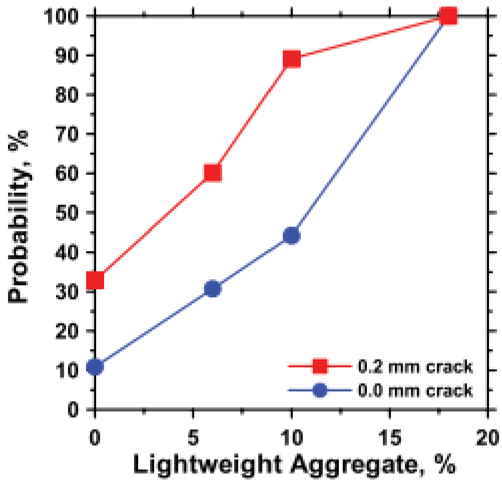


Figure 13. Probability of crack widths being smaller than 0,0mm and 0,2mm with different replacement volumes of LWA. (Henkensiefken et al., 2010 pp 1-6)

2.10.3 Drying shrinkage

Concrete starts to shrink as water which is not consumed by cement hydration leaves the system, that is known as drying shrinkage. The extra water after hydration is required for proper workability and finishing ability, that water is called “water of convenience”. In general, the higher the additional water content, the higher the shrinkage potential. (America’s Cement Manufacturers, 2010, Concrete cracks: A shrinking problem?).

As it can be seen from the figures below, low replacement volumes proved to be quite ineffective in reducing the shrinkage caused both internal and external drying. When higher replacement volumes were used, the shrinkage was reduced significantly, even while the mixtures with LWA lost more mass than the mixture without. Water in the prewetted LWA is available to maintain the saturation of the paste, therefore reducing the drying shrinkage. Because the pore sizes are larger in the LWA compared to cement paste, water is drawn out of the LWAs to the surrounding paste. The emptying of these larger pores will produce much lower capillary stress. Because of that the measured strain and the propensity of the early-age cracking is reduced. (Bentz et al., 2011 pp. 27-29)

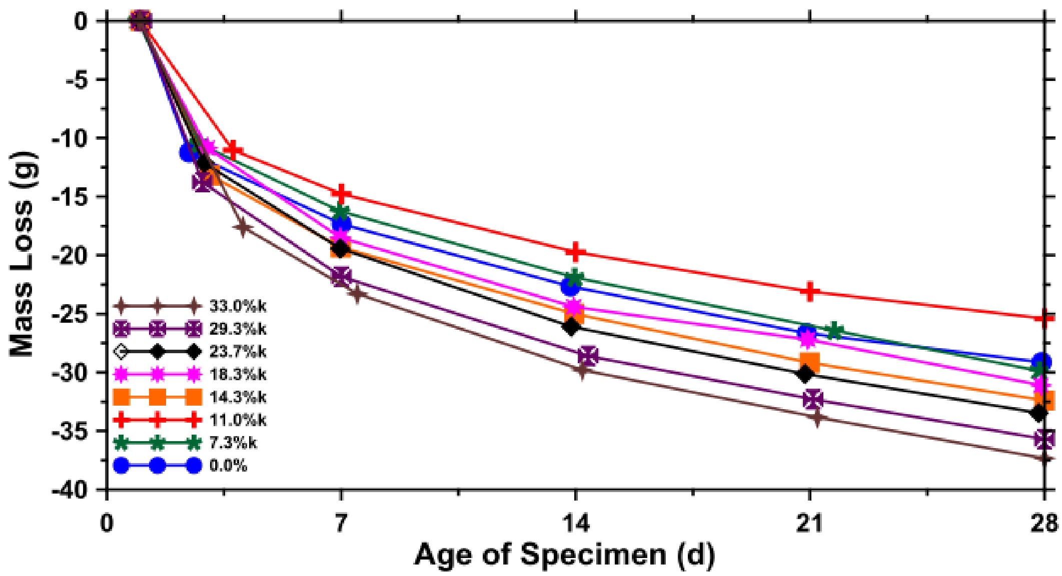


Figure 14. Mass loss of free shrinkage specimens of mortars with different amounts of LWA, unsealed curing conditions. (Bentz et al., 2011 pp. 27-29)

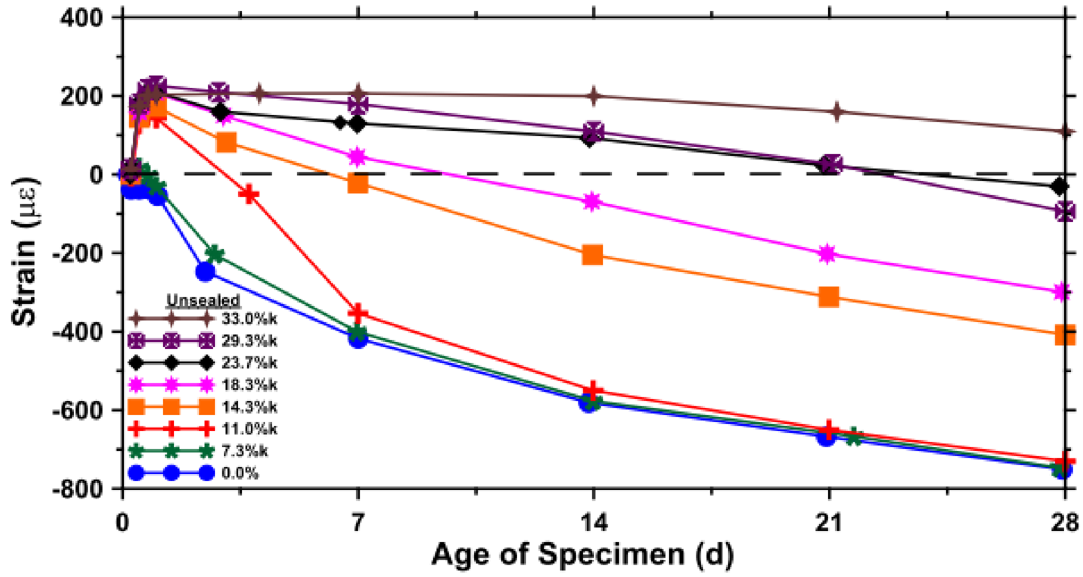


Figure 15. Measured deformation of free shrinkage specimens of mortars with different amounts of LWA, unsealed curing conditions. (Bentz et al., 2011 pp. 27-29)

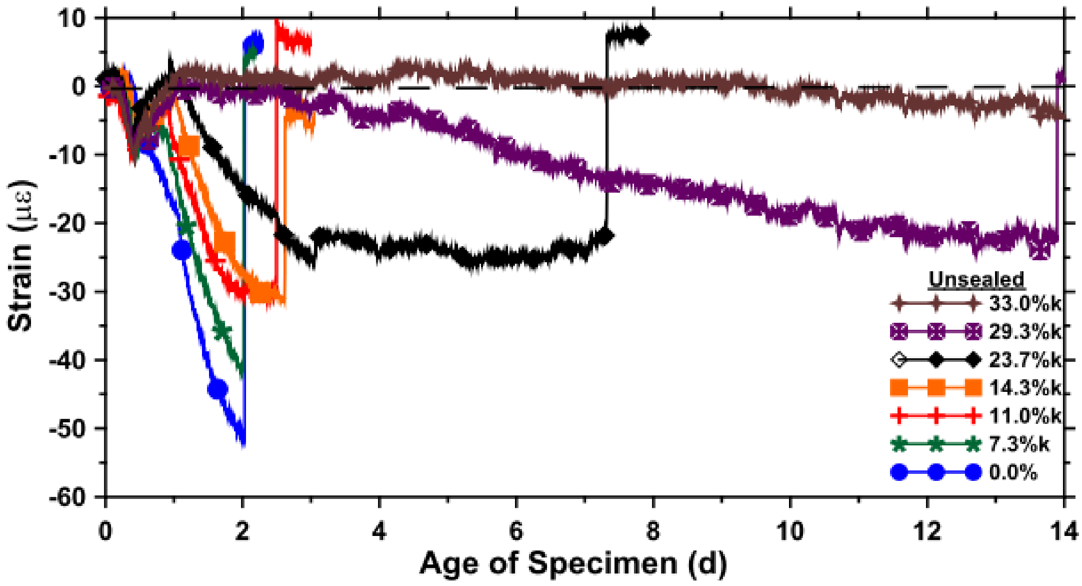


Figure 16. Restrained shrinkage results for mortars with different amounts of LWA, unsealed conditions. A sharp vertical rise indicates cracking. (Bentz et al., 2011 pp. 27-29)

2.11 Summary of previous studies

Previous studies have shown that the major benefits of internally cured concrete are:

- Autogenous shrinkage is reduced or totally eliminated
- Plastic and drying shrinkages are reduced
- Strength can be higher at later ages
- Less permeable
- Better freeze and thaw durability
- Lower penetration of chlorides and other deleterious substances
- Enhanced hydration, leading to denser microstructure
- Improvement of the ITZ
- Reduced both the total porosity and the interconnection of the pore structure of mortar specimens (LWA absorption and desorption: the influence on the microstructure…)
- Lower density

The negatives of using internal curing have also been shown and they consist of the following factors:

- Compressive strength is reduced at early ages and can be reduced also at later ages
- Flexural strength can be reduced

There are also areas that need further study and development and those issues are discussed later in the topic 5.

3 Experimental studies

3.1 Main objectives of the experimental studies

The main objective of the experimental study was to test the concrete mixtures made with prewetted LWA and compare them to the mixture produced without prewetted LWA. Tests include mechanical properties such as compressive strength and flexural / tensile strength and also development of drying shrinkage.

Beside these tests, there was a visual slab observation done. The 700 x 700 x 30 mm^3 slabs were made with all the five mixtures. The cracking and behaviour of those different mixtures was observed.

The mixtures with prewetted LWA are compared to the mixture without LWA, which is called a reference mixture in this thesis. The results of the tests are compared and analysed to have a clear vision what is the impact of internal curing in the concrete properties. There are five different mixtures made, one is the reference mixture and four mixtures are made with LWA:

1. mixture is the reference mixture, without lightweight aggregate
2. mixture, 202,2 kg/m^3 of fine normal weight aggregate (0-2mm) is replaced with pre wetted lightweight aggregate
3. mixture, 202,2 kg/m^3 of 2-4mm normal weight aggregate is replaced with pre wetted lightweight aggregate
4. mixture, 202,2 kg/m^3 of coarse normal weight aggregate (2-8mm) is replaced with pre wetted lightweight aggregate
5. mixture, 202,2 kg/m^3 of both fine and coarse normal weight aggregate (0-8mm) are replaced with lightweight aggregate 202,2 kg/m^3 is 11,5 % of the total aggregate volume.

The percent of LWA is of the total aggregate amount of the concrete mixture. At first, initial experimental studies are made to find the right mixture to do the final xperimental tests. Then in the final experimental studies the mixtures are tested and results are analysed and conclusion are made. After that, there is a comparison made to previous studies. At last, the topics that need further study in the future are discussed.

3.2 Materials and mixture design

Five concrete mixes were made and evaluated with compressive strength, flexural / tensile strength and drying shrinkage tests. There was one reference concrete mix made with no internal curing and four different concrete mixes with internal curing. Concrete mixes were made with Portland Cement type Yleissementti produced by Finnsementti Oy, normal weight granite aggregate, Finnish natural and lightweight aggregate produced by Weber Oy.

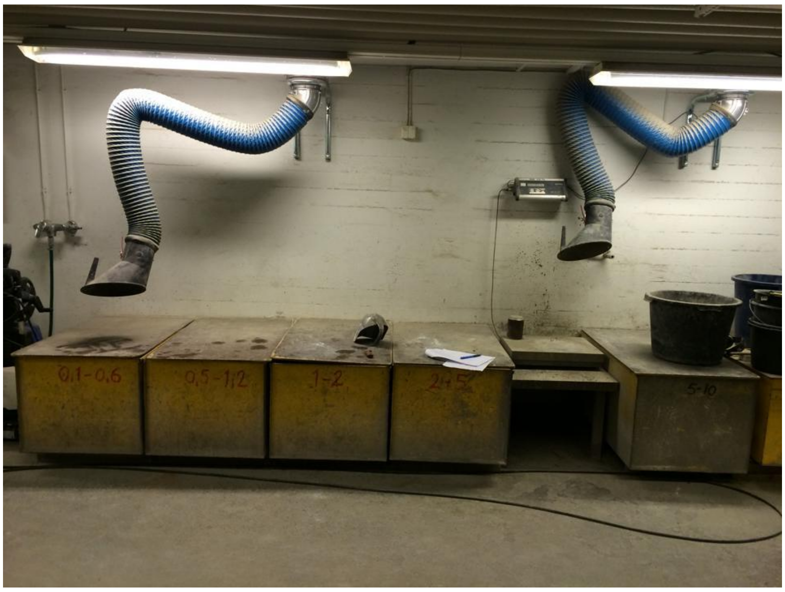


Figure 17. Normal weight aggregates

3.2.1 Characterisation of the LWA

The used lightweight aggregate is Leca lightweight aggregate, manufactured by Weber. Following gradations of lightweight aggregates are used in these studies:

- Round lightweight aggregates: 0-2mm, 2-4mm, 4-8mm.

- Crushed lightweight aggregates: 0-3mm and 3-8mm…

In the final experimental tests, round lightweight aggregates were used as a prewetted .

- Properties of the used Leca lightweight aggregate:

Water absorption of the LWA was calculated as a mass of LWA in dry condition – mass of LWA in wet condition, where wet condition means after 24h immersion. The calculated water absorption was 13,5%. The weight of the lightweight aggregate is following:

- 0-4mm, 325-440 kg/m^3
- 4-8mm, 240-320 kg/m^3

3.3 Prewetting of the LWA

LWA was immersed in water for 24h, see Figure 18. The temperature of the water was 21 Celsius degrees. After the immersion the LWA was taken from the water and the water which was not absorbed to the LWA was used as additional water in the mixture. After the LWA was immersed and taken away from water, the LWA was dried with paper so that the surface of the LWA particles had no moisture, this drying method is called the "paper towel method".
The same method of prewetting the LWA is used in both initial and final experimental studies. The prewetting of the LWA is one of the most important issues when making internally cured concrete and it needs to be done with great care.

Figure 18. LWA was immersed in water for 24h

3.3.1 Absorbtion test

The absorption test made in order to determine the effectiveness and accuracy of the paper towel method to dry the surfaces of the LWA after 24h immersion. Test samples weighting 0,15kg were taken from each LWA gradation; 0-2mm, 2-4mm and 4-8mm. For every gradation following test was made:

1. Samples were oven dried 24h
2. Two 0,15kg samples of LWA were immersed in the 21 degree water for 24 hours.
3. After the 24h immersion:
    a. First sample: Immersed LWA was dried with paper in order to get the surface moisture away. The sample was dried as long as the paper did not get wet.

b. Second sample: Immersed LWA was dried with paper in order to get the surface moisture away and also dried with warm air cooler in order to get also the moisture in the LWA particle away

4. The weight of both samples is taken
5. Both samples placed into oven at temperature of 100 degrees Celsius for 24h

Figure 19. The used oven

6. The weight of both samples was taken
   - From the last weight, when it is compared to the first weight it can be seen how much water there is in the LWA particle which was just dried with paper compared to the one which was air cooled.

This test was carried out in order to ensure that the paper towel method, removed the moisture from the particle surface and not from inner volume.

The results of this test are shown in Figures 20 and 21. The results showed that the paper towel method is useful to get the surface moisture away but at the same time it leaves the internal water in the LWA.

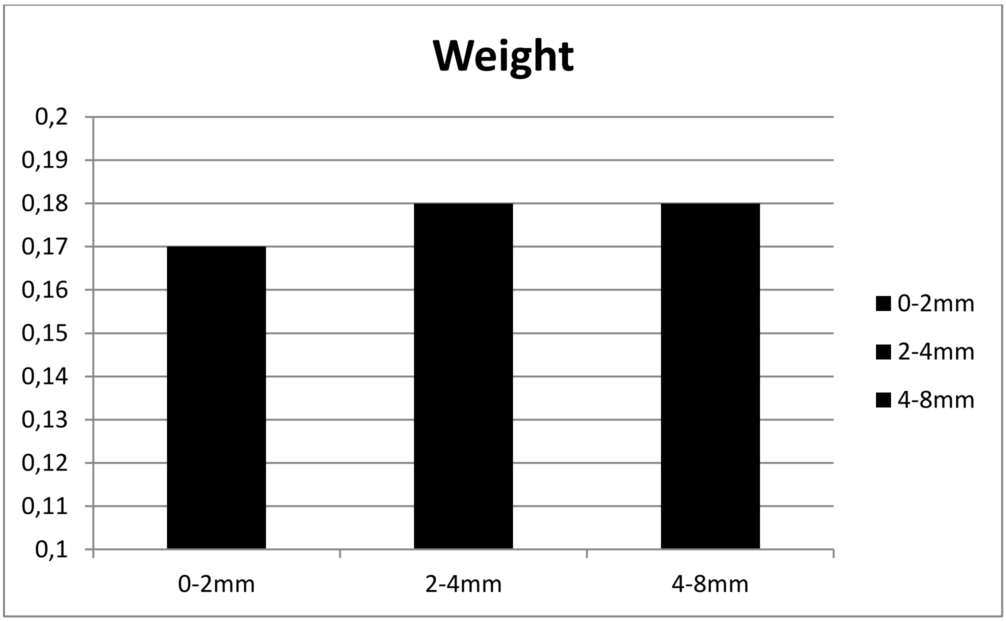
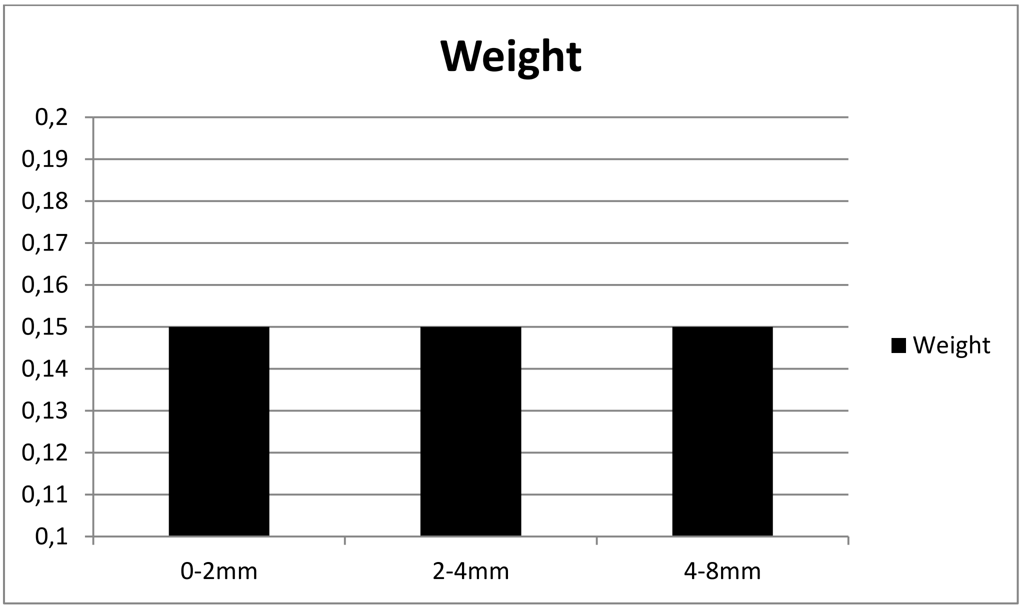


Figure 20. Weight of sand and aggregates after immersion but before drying.



Fiugure 21 Weight of the gradations after drying and air cooling

3.4 Mixing procedure

The concrete was prepared in 20 l Hobart type mixer. The mixing consisted of dry mixing of sand and the coarse aggregate for 30 s before adding the half of the mixing water, all the aggregates and the cement. After one minute the remaining water was added and mixing continued for 2 min 30 seconds.

3.5 Equipment

In the following are some Figures of the used equipment in this study. Pan mixer. The first initial mixture design was made with Pan mixer. The biggest gradation that can be mixed with Pan mixer is 32mm.

Figure 22. Pan mixer

Hobbart mixer. The second initial mixture was made with Hobbart mixer. The maximum gradation that can be used with Hobbart mixer is 10mm and the maximum volume of manufactured concrete is 20 litre.

Figure 23. Hobbart mixer

All the compressive strength tests were made with Toni Processor B 5MN, technical specifications:

Model: Toni Processor B 5MN

- Manufacturer: Zwick Roell group / Toni Technik Baustoffprüfsysteme GmbH
- Type number: 0244
- Maximum force: 5000kN
- Year of manufacture: 1989

Figure 24. The compressive strength tests were made Toni machine

The flexural/tensile strength test were made with RKM 250/50 manufactured by Zwick Roell group / Roell und Korthaus GmbH. Technical specifications are following:

Model: RKM 250/50

Manufacturer: Zwick Roell group / Roell und Korthaus GmbH

Type number: -

Maximum force: 250 kN

Year of manufacture: 1989

Figure 25. The flexural / tensile strength tests were made with Rolli machine.

Figure 26. The used scale

The drying shrinkage was measured with 100mm Demec. Technical specifications of the 100mm Demec are following:

Model: Demec

- Manufacturer: W. H. Mayers & Son, Winsor, Berkshire, England
- Type number: -
- Measure length: 100mm
- Year of manufacture: -
- The number of manufacture: 1328

Figure 27. The drying shrinkage tests were made with 100mm demec.

The samples were stored in the temperature rooms. The RH 95% and 45% temperature rooms were used. The compressive strength samples and flexural / tensile strength samples were stored in the 95 % temperature room and drying shrinkage samples and slabs were stored in the 45 % temperature room.

Figure 28. The RH 95% temperature room

The mould for the slabs were made from plywood. There were four mould made.

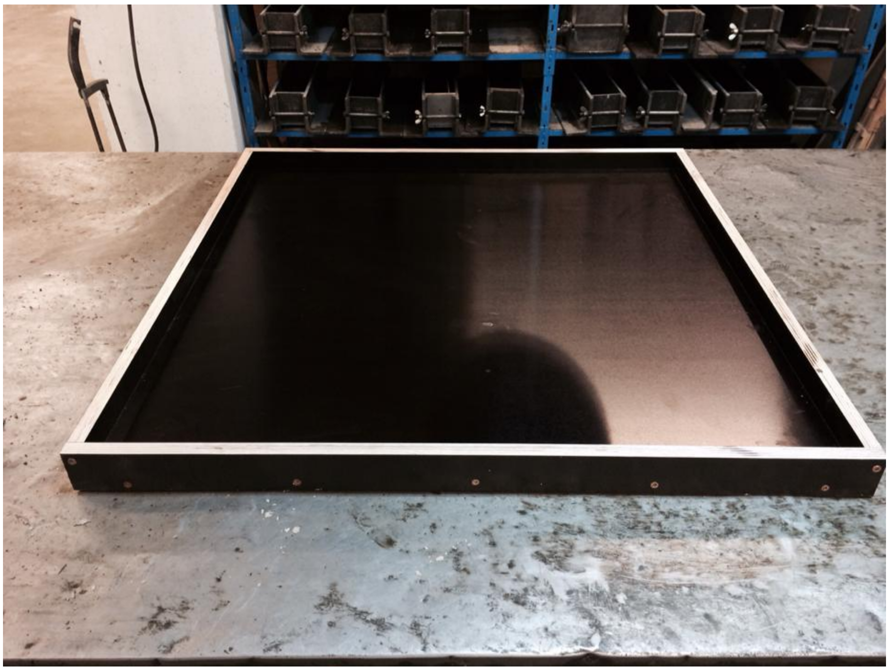


Figure 29. Moulds made for the slabs

3.6 Initial experimental study

The main focus of initial experimental studies was to find the right mixture that can be used to do the final experimental tests.

The initial requirements for the concrete mixture were:

- Strength class K40
- Slump 90mm
- Water / cement ratio 0,50
- Good workability

At first, two basic mixtures without any prewetted LWA were done followed by two initial mixtures made.

3.6.1 Initial mixture design 1

Table 5. The initial mixture design 1

	Initial Mixture Design 1			
Cement			360	kg/m3
Fine aggregate			983	kg/m3
	Filler		55	kg/m3
	0.1-0.6		146	kg/m3
	0.5-1.2		182	kg/m3
	1.0-2.0		218	kg/m3
	2.0-5.0		382	kg/m3
Coarse aggregate			837	kg/m3
	5.0-10.0		400	kg/m3
	8.0-16.0		437	kg/m3
Water			182	kg/m3
Air			20	kg/m3
Total			2362	kg/m3

The more detailed information about mixture design is in the Appendix 1. The needed amount of dry LWA to replace the normal weight aggregate was calculated with Bentz and Snyder equation 2: (Bentz et al., 2011 pp. 5)

$$M_{LWA} = \frac{C_f \times CS \times \alpha_{\max}}{S \times \phi_{LWA}} \qquad \text{(Eq .2)}$$

where,

- M_{LWA} (kg/m3) is the mass of dry LWA that is needed to be prewetted to provide water to the voids, which are created by the chemical shrinkage,
- C_f (kg/m3) is the cement content of the mixture,
- CS (g of water per g of cement) is the chemical shrinkage of the cement, α_{max}(has no unit) is the expected maximum degree of hydration (from 0 to 1),
- S (has no unit) is the expected degree of saturation of the LWA (from 0 to 1)
- Φ_{LWA} (kg of water / kg of dry LWA) is the absorption capacity of the LWA.

The equation can now be written:

360*0,07*1/1*0,135=186,66 kg/m3, which is 10,3 % of the total aggregate volume.

The used value of CS was 0,07, which is a good default value for chemical shrinkage.

In the initial mixture design 1 parts of the fine aggregate and the coarse aggregate were both replaced with prewetted lightweight aggregate:

- 186,66 kg/m3 of the fine aggregate was replaced with prewetted lightweight aggregate, gradation 0-4mm.
- 186,66 kg/m3 of the coarse aggregate was replaced with prewetted lightweight aggregate, gradation 4-8mm.

With the first initial mixture, the drying of the LWA surfaces after the immersion with paper towel method was done too quickly and the LWA was too wet, so the mixture had too much water and was very segregated.

In order to get better mixture the drying of the LWA surfaces after immersion was to be done with much more care.

3.6.2 Initial mixture design 2

The greatest difference in the second initial mixture was that the maximum aggregate size was lowered to 10mm. That was done due to the general simplicity to manufacture concrete in the laboratory with the Hobart mixer.

The second big difference compared to the first initial mixture was that the second mixture had a slump of 150mm instead of 90mm in order to get better flow and workability. More care was taken when drying of LWA surfaces. The strength class was same as in the initial mixture design 1, K40. Water / cement ratio was kept also the same.

	Initial Mixture Design 2			
Cement			390	kg/m3
Fine aggregate			1015	kg/m3
	Filler		53	kg/m3
	0.1-0.6		140	kg/m3
	0.5-1.2		210	kg/m3
	1.0-2.0		245	kg/m3
	2.0-5.0		367	kg/m3
Coarse aggregate			735	kg/m3
	5.0-10.0		735	kg/m3
Water			202	kg/m3
Air			20	kg/m3
Total			2342	kg/m3

Table 6. The initial mixture design 2.

The more detailed information about mixture design is in the Appendix 1. The needed amount of dry LWA to replace the normal weight aggregate was calculated with Bentz and Snyder equation 2:

The equation can now be written:

390*0,07*1/1*0,135=202,2 kg/m3, which is 11,5 % of the total aggregate volume.

the used value of CS was 0,07, which is a good default value for chemical shrinkage. (reference)

In the initial mixture design 2 only the fine aggregate, which was considered to be gradation 0-4mm, was replaced with

- 202,2 kg/m3 of the fine aggregate was replaced with prewetted lightweight aggregate, gradation 0-4mm.

The used amount of water was calculated with the absorption % of the LWA taken into account, the absorption of the used LWA being 13,5%.

Figure 30. The slump of the manufactured concrete was 150mm

This mixture had much better slump and the workability was as required. The strength was also as was required. There were no segregation as can be seen from the Figure 28.

Figure 31. Casted concrete unmoulded

3.7 Main experimental studies

3.7.1 Materials

From the initial experimental studies the mixture design was selected that is used in final experimental studies and thus all five mixtures used in the main part of this study were made with the initial mixture design number 2. Detailed mix design can be found in the attachment XX.

In the final tests as fine aggregates the used gradation was 0-2mm and the coarse aggregate gradation was 2-8mm.

The following five mixes were produced:

1. Reference mix, without lightweight aggregate
2. mix No 2, 202,2 kg/m3 of fine normal weight aggregate (0-2mm) is replaced with pre wetted lightweight aggregate

3. mix No 3, 202,2 kg/m3 of 2-4mm normal weight aggregate is replaced with pre wetted lightweight aggregate
4. mix No 4, 202,2 kg/m3 of coarse normal weight aggregate (2-8mm) is replaced with pre wetted lightweight aggregate
5. mix No 5, 202,2 kg/m3 of both fine and coarse normal weight aggregate (0-8mm) are replaced with lightweight aggregate

The percent of LWA is the total aggregate amount of the concrete mixture.
202,2 kg/m3 is 11,5 % of the total aggregate volume.

3.7.2 Tests

3.7.2.1 Mechanical properties

The compressive strength test was made with all five mixes, including four containing prewetted LWA. The dimensions of samples that were used to measure the compressive strength were $100x100x100mm^3$. 3 specimens per each of the tests made. The compressive tests were made after 1d, 7d and 28d.

The flexural / tensile strength test was made with all five different mixtures, with four of those mixtures containing prewetted LWA. The dimensions of samples that were used to measure the flexural / tensile strength were $100x100x500mm^3$ There were 3 samples made per one test. The test was made after 28d.

3.7.2.2 Drying shrinkage test

The drying shrinkage test was made with all five different mixtures, with four of those mixtures containing prewetted LWA. The drying shrinkage tests were made using 100mm demec. The drying shrinkage was measured daily during 28d period.

Figure 32. Demecs installed in the concrete sample

3.7.2.1 Slab observation test

A additional thin slabs were made in order to visually asses surface cracking potential of the studied concretes.. 700mm x 700mm x 30mm moulds were made and all the five mixtures were casted to them with the same methods and procedures as done earlier in this study. There were no flairs or other external curing used. The moulds were opened after one day and the slabs were taken to the 45 RH temperature room. The slabs were observed for 28days and the possible cracking was marked with a red marker

Figure 33. Casted slab

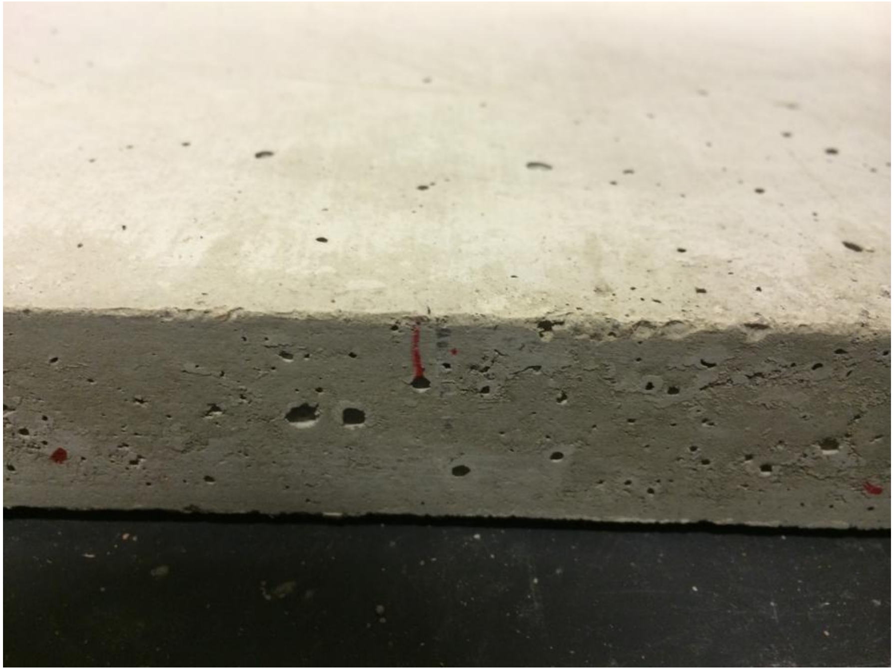


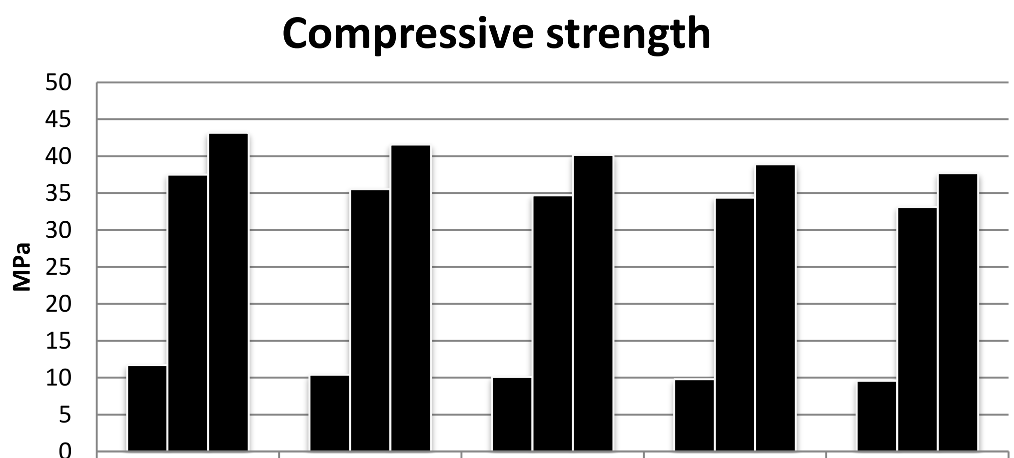
Figure 34. Small cracking in the reference slab

3.8 Test results

3.8.1 Compressive strength

Compressive strength test results show that the internally cured concrete has a slightly lower compressive strength than the reference sample. The compressive strength of the internally cured concrete also depends of the used LWA gradation. As can be seen from the figure 32, which shows the average compressive strength of the three samples of each mixture, the compressive strength of mixtures with low LWA gradations is bigger than the strength produced when bigger LWA gradations are used. The 0-2mm gradation has the greatest compressive strength and the 0-8mm has the weakest compressive strength.

There is some variability with the three samples of each mixture, but generally they are in line. The compressive strength with the four internally cured concrete mixes was in line with the other studies there are concerning the internal curing of concrete. The reference mixture is the strongest and the internally cured mixtures are little weaker. Based on the results, the low LWA gradations are better than bigger LWA gradations in internal curing use.



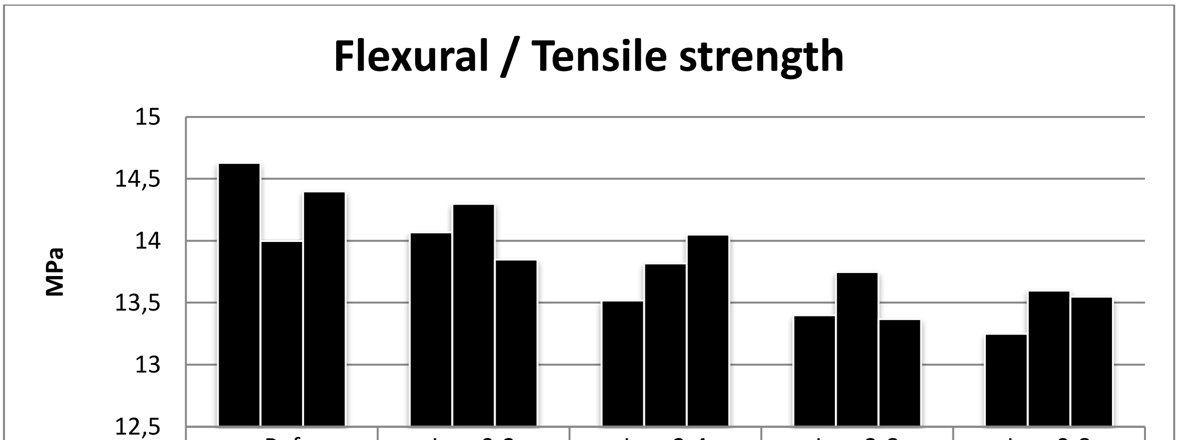
	Ref	0-2mm	2-4mm	2-8mm	0-8mm
■ 1d	11,7	10,4	10,1	9,8	9,6
■ 7d	37,5	35,5	34,7	34,4	33,1
■ 28d	43,2	41,6	40,2	38,9	37,7

Figure 35.The results of the compressive strength tests

3.8.2 Flexural strength / tensile strength

The flexural / tensile strength is similar compared to the compressive strength. As can be seen from the figure 33, the reference mixture has the greatest strength and the internally cured mixtures with low LWA gradation have better strength than the mixtures with higher LWA gradations.

The flexural strength of the internally cured mixes is also in line with the other studies. The reference mixture is the strongest and the internally cured mixtures are little weaker. Based on the results of this thesis and also of the previous studies, the low LWA gradations are better than bigger gradation in internal curing.



	Ref	Lwa 0-2	Lwa 2-4	Lwa 2-8	Lwa 0-8
■ Sample 1	14,63	14,07	13,52	13,4	13,25
■ Sample 2	14	14,3	13,82	13,75	13,6
■ Sample 3	14,4	13,85	14,05	13,37	13,55

Figure 36. The results of the tensile strengrh tests after 28d.

3.8.3 Drying shrinkage

The one of the most important issues regarding internal curing is that internal curing can decrease shrinking. In this thesis only drying shrinkage is observed. As the compressive and flexural strength are little smaller compared to the reference mixture, shrinking is the topic that internal curing has a great impact. As can be seen from the figure 34, 35 and 6, internally cured mixtures have a great impact to the drying shrinkage.

With all mixtures, during the first days the shrinking happens fastest and in the later ages it gets much slower. With LWA 0-2mm mixture the shrinking occurs slowest also in the beginning of shrinking as can be seen from the figures 4,5 and 6. As the gradation of the use LWA gets bigger also the shrinkage occurs faster in the beginning. With both LWA 0-2mm and LWA 2-4mm mixtures the drying shrinkage after 5days is lower compared to the reference mixture.

After 28 days the reference mixture had shrinkage of 35-65mm. The LWA 0-2mm mixture has the greatest impact to the drying shrinkage, after 28 days the samples had a shrinkage of 0,030-0,045mm. After 28 days LWA 2-4mm had shrinkage of 0,040-0,045mm, LWA 2-mm had shrinkage of 0,050mm and LWA 0-8mm had shrinkage of 50-60mm.

The drying shrinkage of the internally cured mixtures is in general similar compared to the previous studies, internal curing decreasing the drying shrinkage of concrete in the span of 28d.

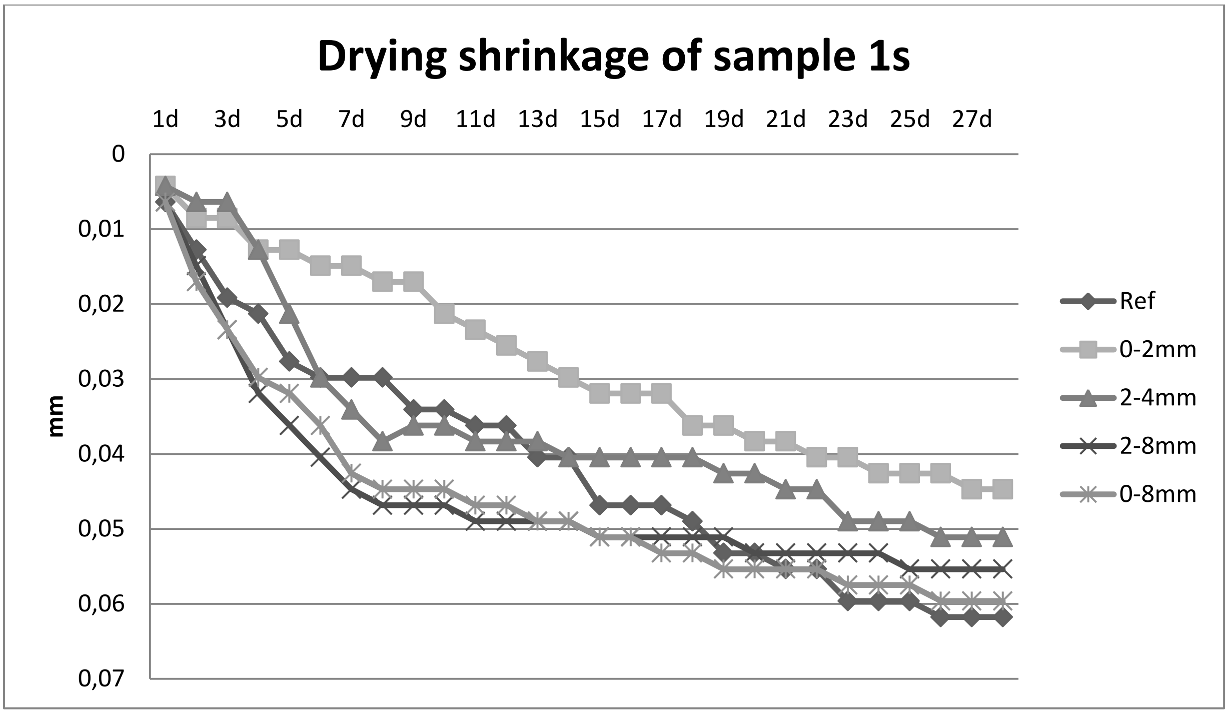


Figure 37. Drying shrinkage of sampe 1s.

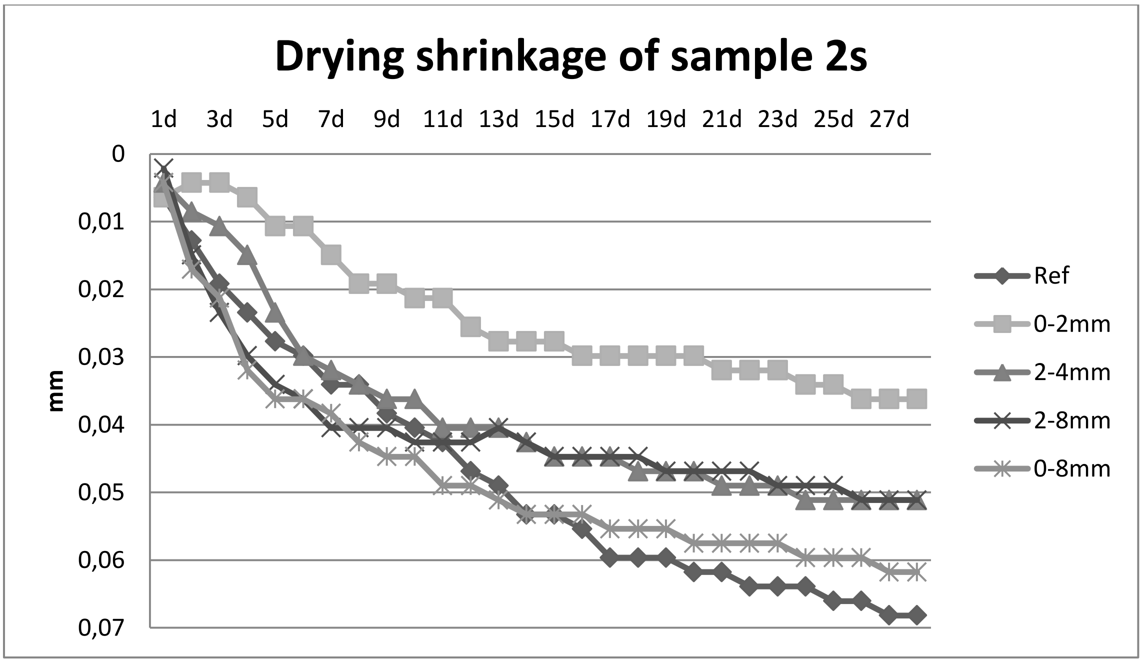


Figure 38. Drying shrinkage of sample 2s.

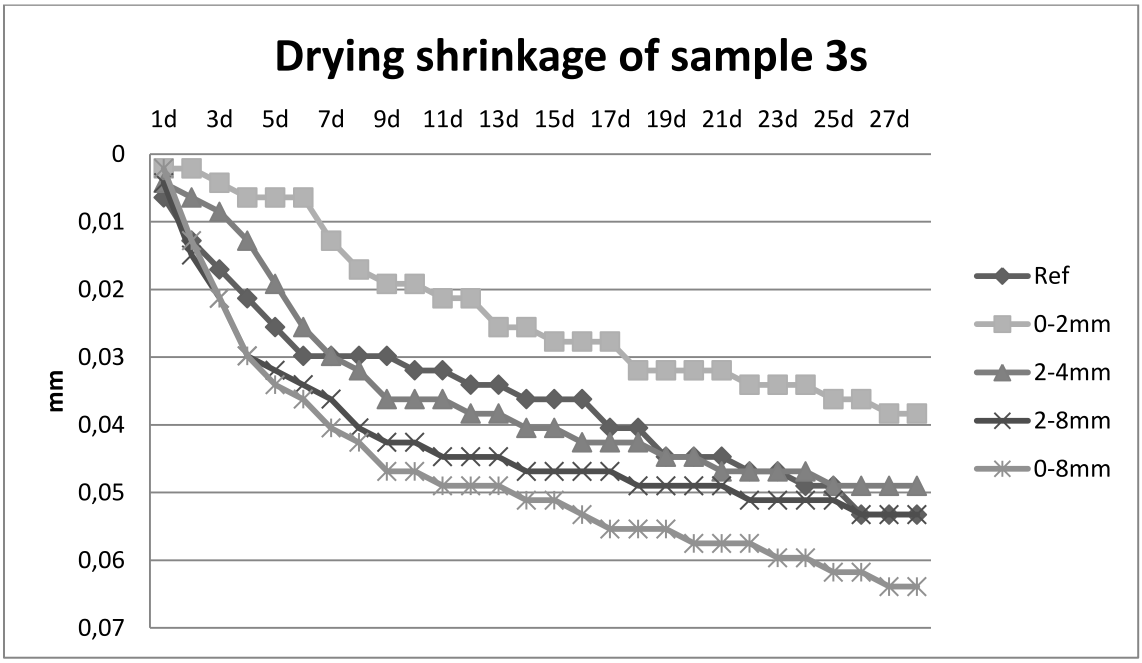


Figure 39. Drying shrinkage of sample 3s.

3.8.4 Slab observation results

The slabs were stored for 28d at 45 % RH in temperature room. In the LWA 0-2mm and 0-4mm there the really small cracks occurred during the first three days and after that the cracking stopped and there occurred no more cracking in them. In the reference mixture the cracking occurred during the first five days and after that it was almost stopped but some small cracking still continued and existed. In the LWA 0-8mm and 2-8mm mixtures the cracking was similar compared to the reference mixture, the cracking occurred during the first five days and some small cracking continued after that, but it ended before the reference mixture's cracking.

Also based on these slab observations, the gradation from 0-4mm was the best in internal curing use. In the LWA mixtures 0-8 mm and 2-8 mm the cracking in the slabs is similar compared to the reference mixture.

4 Conclusions

4.1 Prewetting of the LWA

The prewetting of the lightweight aggregate is one of the most important factors in the making of internally cured concrete. It is extremely important to prewet the LWA diligently and with great care.

In this thesis the prewetting was made with 24h immersion and surface dried with the paper towel method. After the LWA was immersed and taken away from the immersion water, the LWA was dried so that the surface of the LWA particles had not moisture. It is tricky to find the right moment when the surfaces of the particles have not any moisture and on the other hand that the inside of the LWA particles does not dry.

The prewetting of the LWA should be considered one of the main topics that need further research and study in order to develop internally cured concrete.

4.2 Test results

4.2.1 Compressive strength

The compressive strength of mixtures where lightweight aggregates were used was reduced little as compared to the reference mixture. The LWA 0-2 mixture was the closest to the reference mixture as can be seen from the test results.

The study shows that the lightweight aggregate gradation from 0-4 is the best option to use in order to get a good compressive strength. The compressive strength of LWA 0-2 mixture was reduced by 2-3% as compared to the reference mixture. LWA 2-4 mixture had a compressive strength reduced by 5% compared to the reference mixture. The two mixtures, namely LWA 2-8 and LWA 0-8 mixture, compressive strength was reduced by 5-10 % as compared to the reference mixture.

It can be concluded that strengthening effect on hydration provided by internal curing water from LWA does not cover the effect of replacement of normal weight aggregate with lightweight aggregate, but in general all the internally cured mixtures have a good compressive strength.

4.2.2 Flexural strength / tensile strength

The mixtures where lightweight aggregates were used had slightly or little more reduced flexural strength as compared to the reference mixture. Generally the reference mixture was stronger than the mixtures with LWA.

The LWA 0-2 mixture was the strongest of all internally cured mixtures. The LWA 2-4 mixture was second strongest, LWA 2-8 was third and the LWA 0-8 mixture was the weakest mixture of the internally cured mixtures.

In general all the internally cured mixtures had a good flexural strength.

4.2.3 Drying shrinkage

From the drying shrinkage test results it can be seen that in general the shrinkage is lower in all internally cured mixtures compared to the reference mixture in the span of 28d. In the LWA 0-2 mixture the shrinkage is lowest and as the gradation of used lightweight aggregate increases, also the shrinkage increases.

The use of LWA has a great effect on the drying shrinkage of the concrete. As the results show the prewetted LWA decreases the drying shrinkage. All the gradations (0-8mm) have that effect.

The ability to reduce shrinking is the greatest benefit of internal curing. As the mechanical properties are slightly reduced, they are still on good level and the concrete is strong enough. As the shrinking is reduced, the cracking reduces, which is really beneficial. As the previous studies have shown, the autogenous shrinking can be almost zero when internal curing is used. As the experimental studies around the world have shown, internal curing works also in practise, not only in laboratory.

5 Future studies

Further studies should include following topics:

- The prewetting of the LWA should be studied. It is really important to do the prewetting process as thoroughly as possible.
- The autogenous and plastic shrinkage need to be studied also, as this thesis concentrates only to the drying shrinkage.
- The time when internal water is released from the LWA is very important to know exactly and it should be observed in the future.
- The spreading of the LWA in the three dimensional concrete need further studying.
- Internal curing should be studied also with low water / cement mixtures and high strength concretes.
- The interfacial transition zone should be observed

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Appendix 1.

Initial mixture design 1.

			Aggregate granularity									
	Filter mm		0,125	0,25	0,5	1	2	4	8	16	32	64
a	FILLER, Astara		68,9	89,7	96,5	98,9	99,4	99,7	100	100	100	100
b	0,1 - 0,6		4	30	88	100	100	100	100	100	100	100
c	0,5 - 1,2		0	3	23	96	100	100	100	100	100	100
d	1 - 2		0	0	1	13	86	100	100	100	100	100
e	2 - 5		0	0	0	0	1	40	100	100	100	100
f	5 - 10		0	0	0	0	0	2	48	100	100	100
g	8 - 16		0	0	0	0	0	0	5	96	100	100

Table 1.Aggregate granularity

			Aggregates combination, initial design mixture 1										
	Filter mm	%	0,125	0,25	0,5	1	2	4	8	16	32	64	H
a	Filler	3	2,067	2,691	2,895	2,967	2,982	2,991	3	3	3	3	28,593
b	0,1 - 0,6	8	0,32	2,4	7,04	8	8	8	8	8	8	8	65,76
c	0,5 - 1,2	10	0	0,3	2,3	9,6	10	10	10	10	10	10	72,2
d	1 - 2	12	0	0	0,12	1,56	10,32	12	12	12	12	12	72
e	2 - 5	21	0	0	0	0	0,21	8,4	21	21	21	21	92,61
f	5 - 10	22	0	0	0	0	0	0,44	10,56	22	22	22	77
g	8 - 16	24	0	0	0	0	0	0	1,2	23,04	24	24	72,24
	Combined	100	2,387	5,391	12,355	22,127	31,512	41,831	65,76	99,04	100	100	480,403
			2					42					

Table 2. Aggregate combination

				Initial design mixture 1								
Ingredients											Work mixture kg/m3	Dose m3
	kg/m3		%	Density	dm3/m3	kg/m3	Total %	absorbed %	Effective water %	Effective water kg		0,015
Cement	360			3,1							360	5,4
Aggregate		a	3			54,6	0	0	0	0	54,6	0,819
		b	8			145,6	0	0	0	0	145,6	2,184
	1820	c	10			182	0	0	0	0	182	2,73
		d	12			218,4	0	0	0	0	218,4	3,276
		e	21			382,2	0	0	0	0	382,2	5,733
		f	22			400,4	0	0	0	0	400,4	6,006
		g	24			436,8	0	0	0	0	436,8	6,552
Water	182			1000						0	182	2,73
Air	20											0
Total	2362										2362	35,43

Table 3. Initial mixture design 1

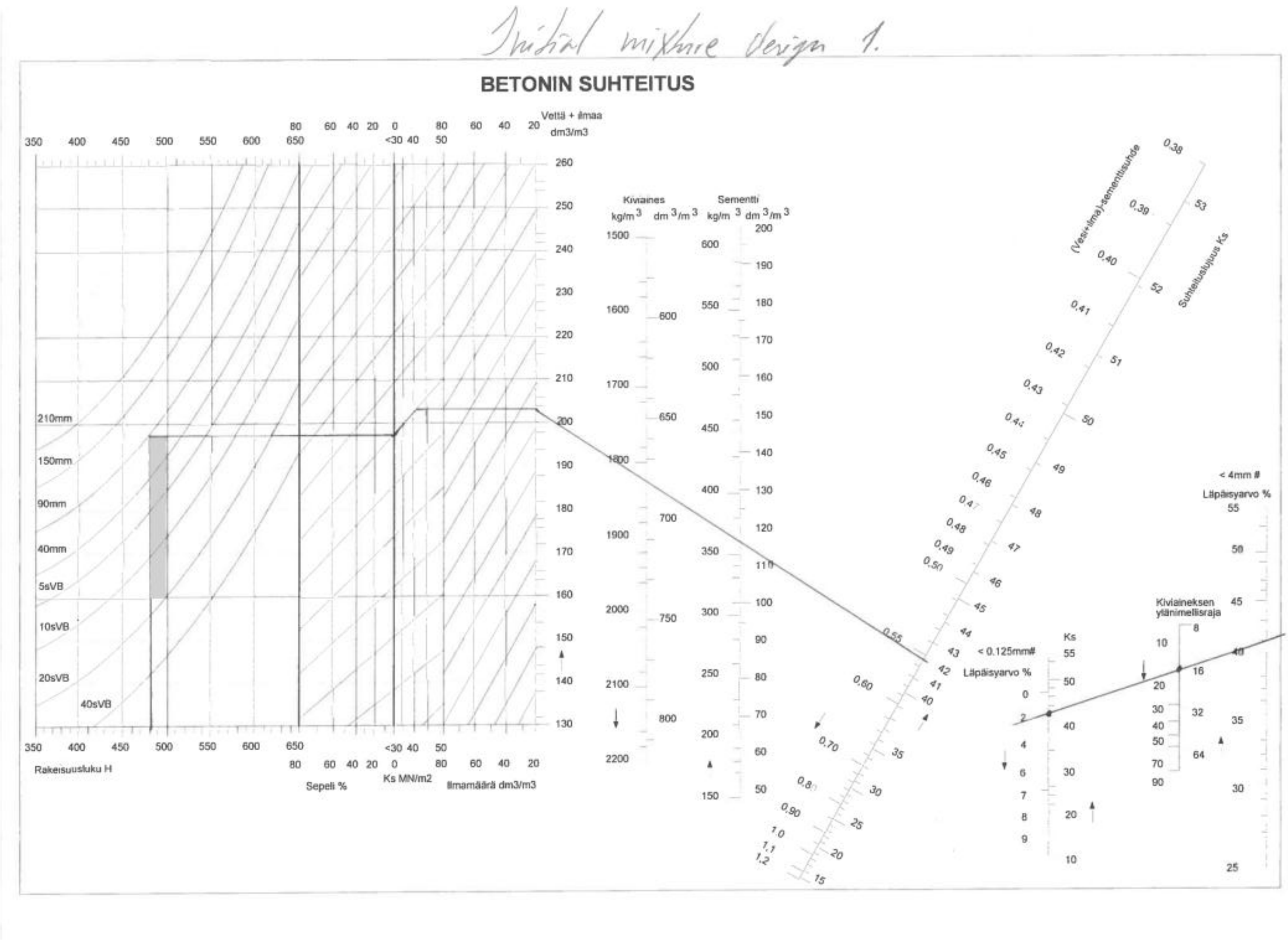

Table 4. Initial mixture design 1

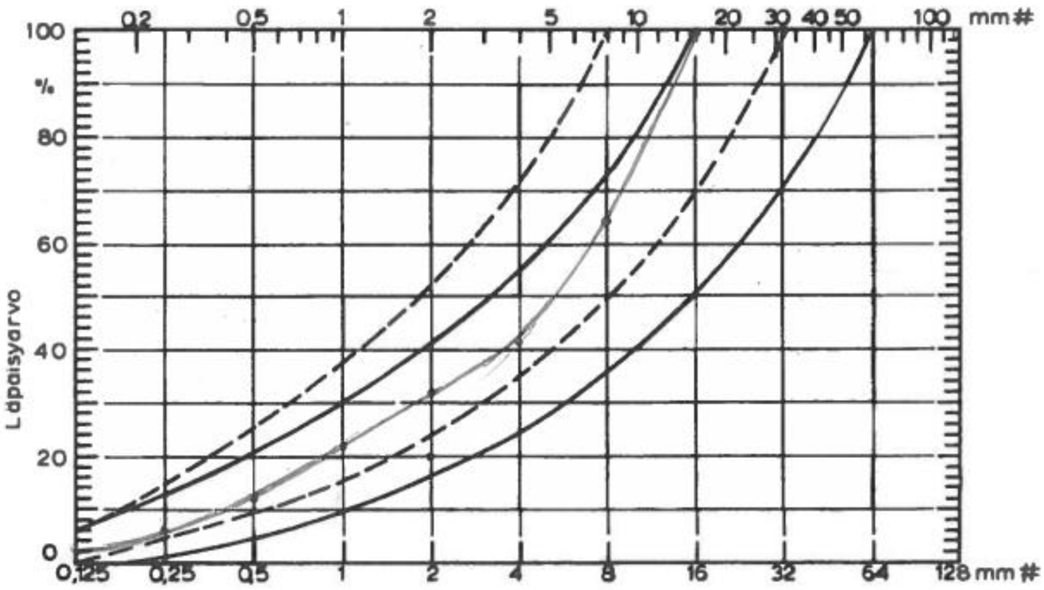

Table 5. The gradation curve

Initial mixture design 2

			Aggregate granularity									
	Filter mm		0,125	0,25	0,5	1	2	4	8	16	32	64
a	FILLER, Astara		68,9	89,7	96,5	98,9	99,4	99,7	100	100	100	100
b	0,1 - 0,6		4	30	88	100	100	100	100	100	100	100
c	0,5 - 1,2		0	3	23	96	100	100	100	100	100	100
d	1 - 2		0	0	1	13	86	100	100	100	100	100
e	2 - 5		0	0	0	0	1	40	100	100	100	100
f	5 - 10		0	0	0	0	0	2	48	100	100	100
g	8 - 16		0	0	0	0	0	0	5	96	100	100

Table 6.Aggregate granularity

			Aggregates combination, initial design mixture 2										
	Seula mm	%	0,125	0,25	0,5	1	2	4	8	16	32	64	H
a	Filleri	3	2,067	2,691	2,895	2,967	2,982	2,991	3	3	3	3	28,593
b	0,1 - 0,6	8	0,32	2,4	7,04	8	8	8	8	8	8	8	65,76
c	0,5 - 1,2	12	0	0,36	2,76	11,52	12	12	12	12	12	12	86,64
d	1 - 2	14	0	0	0,14	1,82	12,04	14	14	14	14	14	84
e	2 - 5	21	0	0	0	0	0,21	8,4	21	21	21	21	92,61
f	5 - 10	42	0	0	0	0	0	0,84	20,16	42	42	42	147
g	8 - 16	0	0	0	0	0	0	0	0	0	0	0	0
	Combined	100	2,387	5,451	12,835	24,307	35,232	46,231	78,16	100	100	100	504,603
			2					46					

Table 7.Aggregate combination

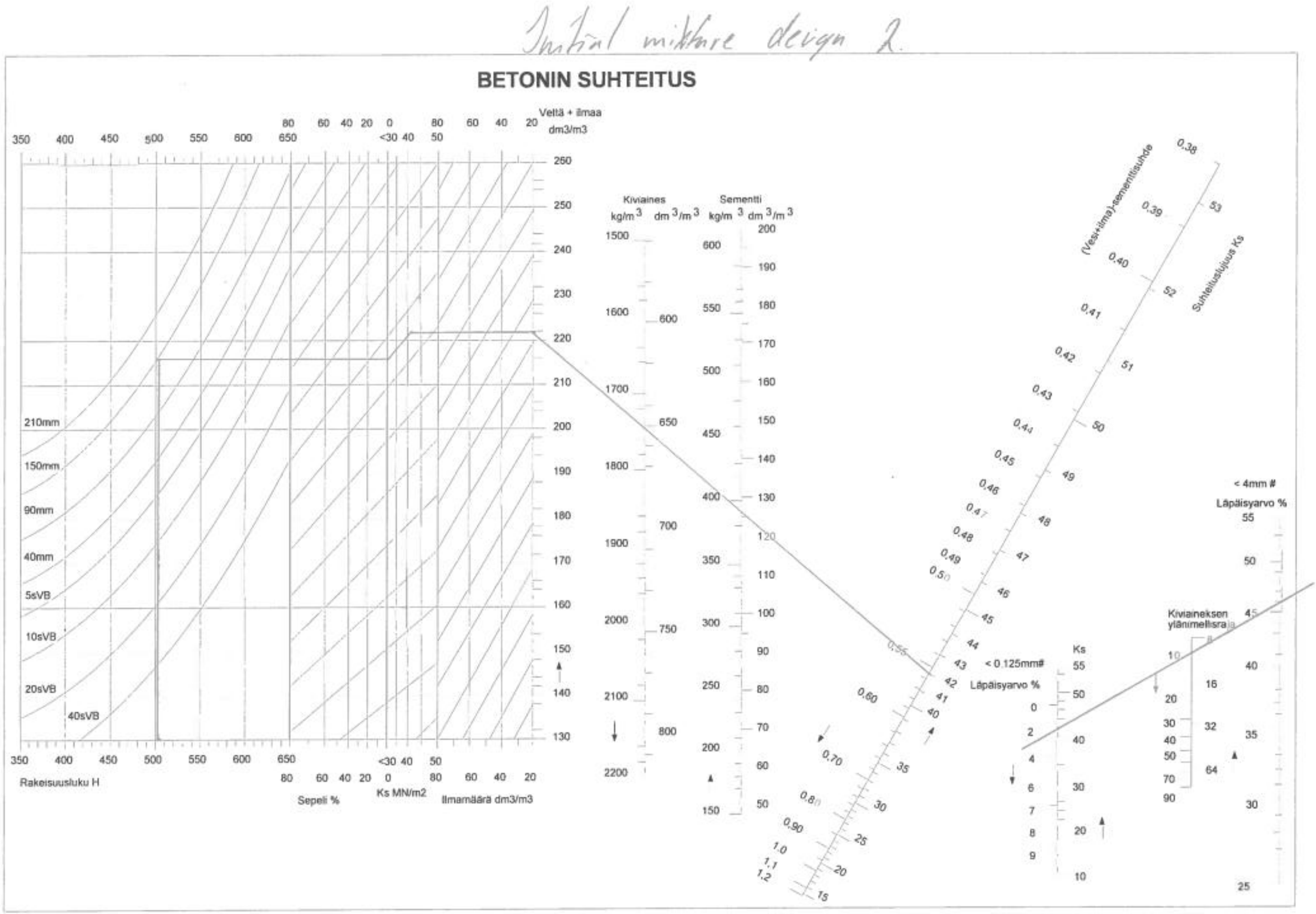

Table 8. Initial mixture design 2

				Initial design mixture 2								
Ingredients											Work mixture kg/m3	Dose m3
	kg/m3		%	Density	dm3/m3	kg/m3	Total %	absorbed%	Effective water %	Effective water kg		0,01
Cement	390			3,1							390	3,9
Aggregate		a	3			52,5	0	0	0	0	52,5	0,525
		b	8			140	0	0	0	0	140	1,4
	1750	c	12			210	0	0	0	0	210	2,1
		d	14			245	0	0	0	0	245	2,45
		e	21			367,5	0	0	0	0	367,5	3,675
		f	42			735	0	0	0	0	735	7,35
		g	0			0	0	0	0	0	0	0
Water	202			1000						0	202	2,02
Air	20											0
Total	2342										2342	23,42

Table 9.Initial mixture design 2

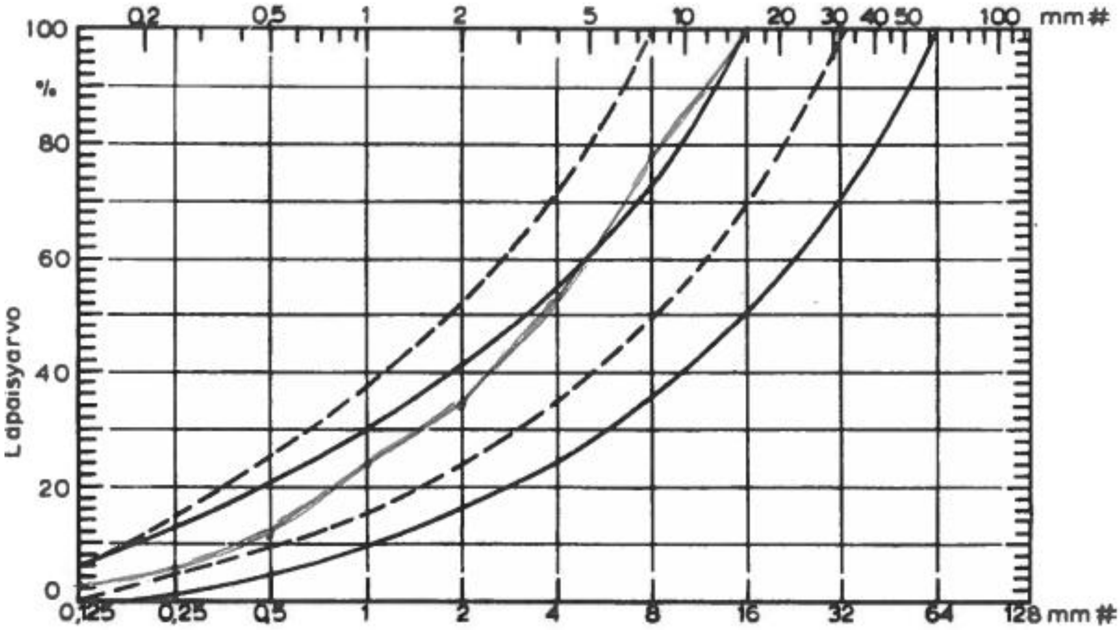

Table 10.The gradation curve

The results of compressive strength tests are:

Mixture 1, which was the reference mixture:

1d: sample 1: 11,16; sample 2: 11,57; sample 3: 12,35

7d: sample 1: 37,38; sample 2: 36,45: sample 3: 38,55

28d: sample 1: 42,64; sample 2; 43,15; sample 3: 43,80

Average weight of specimens was 2 203g.

Mixture 2, LWA 0-2:

1d: sample 1: 10,72; sample 2: 10,30; sample 3: 10,05

7d: sample 1: 35,40; sample 2: 34,50: sample 3: 36,74

28d: sample 1: 41,47; sample 2; 42,12; sample 3: 41,33

Average weight of specimens was 2 150g.

Mixture 3, LWA 2-4:

1d: sample 1: 10,46; sample 2: 10,22; sample 3: 9,74

7d: sample 1: 35,21; sample 2: 34,56: sample 3: 34,35

28d: sample 1: 40,44; sample 2; 40,11; sample 3: 40,03

Average weight of specimens was 2 116g.

Mixture 4, LWA 2-8:

1d: sample 1: 10,10; sample 2: 9,77; sample 3: 9,45

7d: sample 1: 35,20; sample 2: 33,30: sample 3: 34,83

28d: sample 1: 39,24; sample 2; 38,45; sample 3: 39,06

Average weight of specimens was 2 105g.

Mixture 5, LWA 0-8:

1d: sample 1: 9,66; sample 2: 9,87; sample 3: 9,25

7d: sample 1: 32,68; sample 2: 32,35: sample 3: 34,15

28d: sample 1: 38,44; sample 2; 37,15; sample 3: 37,50

Average weight of specimens was 2 068g.

The results of flexural strength tests are:

Mixture 1, which is the reference mixture:

28d: sample 1: 14,63 kN; sample 2: 14,00 kN; sample 3: 14,40 kN

average mass of specimens: 11 018g

Mixture 2, LWA 0-2:

28d: sample 1: 14,07 kN; sample 2: 14,30 kN; sample 3: 13,85 kN

Average mass of specimens: 10 510g

Mixture 3, LWA 2-4:

28d: sample 1: 13,52 kN; sample 2: 13,82 kN; sample 3: 14,05 kN

average mass of specimens: 10 204g

Mixture 4, LWA 2-8:

28d: sample 1: 13,40 kN; sample 2: 13,75 kN; sample 3: 13,37 kN

average mass of specimens: 10 105g

<u>Mixture 5, LWA 0-8:</u>

28d: sample 1: 13,25 kN; sample 2: 13,60 kN; sample 3: 13,55 kN

average mass of specimens: 9 920g

The results of drying shrinkage tests are following:

Reference mixture:

	Drying shrinkage	mm	
	Reference mixture		
	Sample 1	Sample 2	Sample 3
1d	0,00639	0,00639	0,00639
2d	0,01278	0,01278	0,01278
3d	0,01917	0,01917	0,01704
4d	0,0213	0,02343	0,0213
5d	0,02769	0,02769	0,02556
6d	0,02982	0,02982	0,02982
7d	0,02982	0,03408	0,02982
8d	0,02982	0,03408	0,02982
9d	0,03408	0,03834	0,02982
10d	0,03408	0,04047	0,03195
11d	0,03621	0,0426	0,03195
12d	0,03621	0,04686	0,03408
13d	0,04047	0,04899	0,03408
14d	0,04047	0,05325	0,03621
15d	0,04686	0,5325	0,03621
16d	0,04686	0,05538	0,03621
17d	0,04686	0,05964	0,04047
18d	0,04899	0,05964	0,04047
19d	0,05325	0,05964	0,04473
20d	0,05325	0,06177	0,04473
21d	0,05538	0,06177	0,04473
22d	0,05538	0,0639	0,04686
23d	0,05964	0,0639	0,04686
24d	0,05964	0,0639	0,04899
25d	0,05964	0,6603	0,04899
26d	0,06177	0,6603	0,5325
27d	0,06177	0,6816	0,5325
28d	0,06177	0,6816	0,5325

LWA 0-2 mixture:

		Drying shrinkage		mm		
		Lwa 0-2 mixture				
		Sample 1		Sample 2		Sample 3
1d		0,00426		0,00639		0,00213
2d		0,00852		0,00426		0,00213
3d		0,00852		0,00426		0,00426
4d		0,01278		0,00639		0,00639
5d		0,01278		0,01065		0,00639
6d		0,01491		0,01065		0,00639
7d		0,01491		0,01491		0,01278
8d		0,01704		0,01917		0,01704
9d		0,01704		0,01917		0,01917
10d		0,0213		0,0213		0,01917
11d		0,02343		0,0213		0,0213
12d		0,02556		0,02556		0,0213
13d		0,02769		0,02769		0,02556
14d		0,02982		0,02769		0,02556
15d		0,03195		0,02769		0,02769
16d		0,03195		0,02982		0,02769
17d		0,03195		0,02982		0,02769
18d		0,03621		0,02982		0,03195
19d		0,03621		0,02982		0,03195
20d		0,03834		0,02982		0,03195
21d		0,03834		0,03195		0,03195
22d		0,04047		0,03195		0,03408
23d		0,04047		0,03195		0,03408
24d		0,0426		0,03408		0,03408
25d		0,0426		0,03408		0,03621
26d		0,0426		0,03621		0,03621
27d		0,04473		0,03621		0,03834
28d		0,04473		0,03621		0,03834

LWA 2-4 mixture:

		Drying shrinkage		mm		
		Lwa 2-4 mixture				
		Sample 1		Sample 2		Sample 3
1d		0,00426		0,00426		0,00426
2d		0,00639		0,00852		0,00639
3d		0,00639		0,01065		0,00852
4d		0,01278		0,01491		0,01278
5d		0,0213		0,02343		0,01917
6d		0,02982		0,02982		0,02556
7d		0,03408		0,03195		0,02982
8d		0,03834		0,03408		0,03195
9d		0,03621		0,03621		0,03621
10d		0,03621		0,03621		0,03621
11d		0,03834		0,04047		0,03621
12d		0,03834		0,04047		0,03834
13d		0,03834		0,04047		0,03834
14d		0,04047		0,0426		0,04047
15d		0,04047		0,04473		0,04047
16d		0,04047		0,04473		0,0426
17d		0,04047		0,04473		0,0426
18d		0,04047		0,04686		0,0426
19d		0,0426		0,04686		0,04473
20d		0,0426		0,04686		0,04473
21d		0,04473		0,04899		0,04686
22d		0,04473		0,04899		0,04686
23d		0,04899		0,04899		0,04686
24d		0,04899		0,05112		0,04686
25d		0,04899		0,05112		0,04899
26d		0,05112		0,05112		0,04899
27d		0,05112		0,05112		0,04899
28d		0,05112		0,05112		0,04899

<u>LWA 2-8 mixture:</u>

		Drying shrinkage		mm		
		Lwa 2-8 mixture				
		Sample 1		Sample 2		Sample 3
1d		0,00639		0,00213		0,00426
2d		0,01491		0,01491		0,01491
3d		0,02343		0,02343		0,0213
4d		0,03195		0,02982		0,02982
5d		0,03621		0,03408		0,03195
6d		0,04047		0,03621		0,03408
7d		0,04473		0,04047		0,03621
8d		0,04686		0,04047		0,04047
9d		0,04686		0,04047		0,0426
10d		0,04686		0,0426		0,0426
11d		0,04899		0,0426		0,04473
12d		0,04899		0,0426		0,04473
13d		0,04899		0,04047		0,04473
14d		0,04899		0,0426		0,04686
15d		0,05112		0,04473		0,04686
16d		0,05112		0,04473		0,04686
17d		0,05112		0,04473		0,04686
18d		0,05112		0,04473		0,04899
19d		0,05112		0,04686		0,04899
20d		0,05325		0,04686		0,04899
21d		0,05325		0,04686		0,04899
22d		0,05325		0,04686		0,05112
23d		0,05325		0,04899		0,05112
24d		0,05325		0,04899		0,05112
25d		0,05538		0,04899		0,05112
26d		0,05538		0,05112		0,05325
27d		0,05538		0,05112		0,05325
28d		0,05538		0,05112		0,05325

LWA 0-8 mixture:

		Drying shrinkage		mm		
		Lwa 0-8 mixture				
		Sample 1		Sample 2		Sample 3
1d		0,00639		0,00426		0,00213
2d		0,01704		0,01704		0,01278
3d		0,02343		0,0213		0,0213
4d		0,02982		0,03195		0,02982
5d		0,03195		0,03621		0,03408
6d		0,03621		0,03621		0,03621
7d		0,0426		0,03834		0,04047
8d		0,04473		0,0426		0,0426
9d		0,04473		0,04473		0,04686
10d		0,04473		0,04473		0,04686
11d		0,04686		0,04899		0,04899
12d		0,04686		0,04899		0,04899
13d		0,04899		0,05112		0,04899
14d		0,04899		0,05325		0,05112
15d		0,05112		0,05325		0,05112
16d		0,05112		0,05325		0,05325
17d		0,05325		0,05538		0,05538
18d		0,05325		0,05538		0,05538
19d		0,05538		0,05538		0,05538
20d		0,05538		0,05751		0,05751
21d		0,05538		0,05751		0,05751
22d		0,05538		0,05751		0,05751
23d		0,05751		0,05751		0,05964
24d		0,05751		0,05964		0,05964
25d		0,05751		0,05964		0,06177
26d		0,05964		0,05964		0,06177
27d		0,05964		0,06177		0,0639
28d		0,05964		0,06177		0,0639